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THE GENESIS OF THE MACKAY COPPER DEPOSITS, IDAHO.[1]

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INTRODUCTION.

The garnetiferous copper deposits near Mackay, Idaho, are of particular interest because: (1) the ore bodies occur well

[1] Published with the permission of the Director of the U. S. Geological Survey.

within a granite porphyry mass; (2) the principal metamorphism is later than the solidification of the porphyry inclosing the ore shoots; (3) engulfed blocks of limestone determined the loci of metamorphism; (4) the garnet rock is both of granite-porphyry and limestone derivation; and (5) the magma clearly supplied great quantities of iron, alumina, and silica to the contact rocks in addition to the constituents of the ore minerals.

Mackay, the principal settlement in the Alder Creek mining district, is situated in east-central Idaho. The copper deposits occurring here came into prominence in 1900 when they were acquired by the White Knob Mining Company, which during the next six years was reorganized many times under the same general name, each company a failure more disastrous than the last. Since 1907, however, the mine has been worked most of the time on a paying basis.

The deposits were described in 1907 in a joint paper based upon the field work of C. G. Gunther and the laboratory studies of J. F. Kemp.[1] These authors discuss at some length the contact metamorphism which characterizes the deposits. As a result of differences in field observation the present studies have led to conclusions, some of which are fundamentally different from those of the earlier writers. Their paper, however, has been of great assistance in the present investigation, and their analyses and descriptions of special features have been freely drawn upon. The present writer differs from them in believing that (1) the "quartz porphyry" is unquestionably a marginal phase of the "granite" which instead of being Archean is late Cretaceous in age; (2) the garnetization took place after the consolidation of at least the outer few hundred feet of the magma instead of while it was still viscous, and (3) engulfed blocks of limestone determined the loci of metamorphism.

The writer spent twelve days in the district in August and September, 1912, and revisited the deposits for four days in June, 1913. The final report will appear as a bulletin of the U. S. Geological Survey.

[1] Kemp, J. F., and Gunther, C. G., "The White Knob copper deposits, Mackay, Idaho," *Bi-Monthly Bull., Am. Inst. Min. Eng.*, No. 14, 1907, pp. 301–328.

GENERAL GEOLOGY.

The Alder Creek mining district comprises a segment of the northeastern slope of the rugged mountain range which borders Big Lost River valley on the southwest. From Mackay at an elevation of 5,888 feet the surface rises, rather gently for three miles, but precipitously beyond, and finally leads to the summit

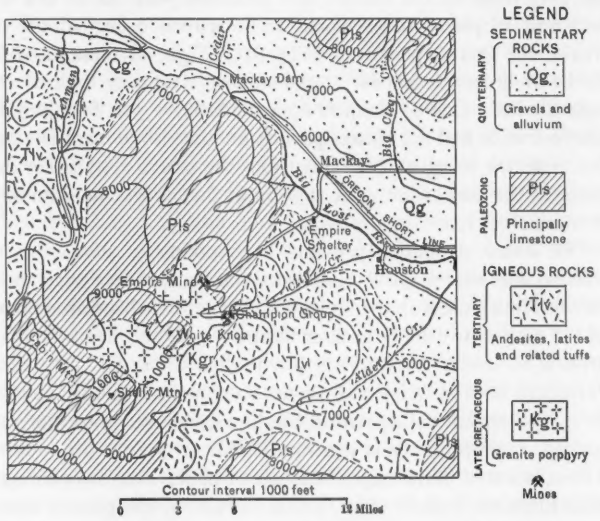

FIG. 80. Sketch map showing geology and topography of the Alder Creek district, Idaho.

of White Knob, a great mass of marble 9,600 feet above sea. The general slope is trenched by several canyons and ravines, most important among them the canyon of Cliff Creek, which heads against White Knob and flows through the central portion of the district (see Fig. 80).

The rock formations of the district comprise a thick series of Carboniferous limestone, intruded by a batholithic mass of late Cretaceous granite porphyry and these traversed by narrow

dikes of trachyte porphyry. A thick series of lavas and tuffs of Miocene age occupy erosion depressions in the eastern and southern parts of the district.

SEDIMENTARY ROCKS.

The limestone beds, comprising the sedimentary rocks, crop out over most of the eastern and southern portions of the district and in places large blocks of limestone occur within the area of the granite porphyry (Fig. 81). Eight of these engulfed blocks of limestone appear at the surface within an area of one square mile. One of them is approximately 1,500 feet long by 500 feet wide and the closest part of another large mass is 1,200 feet from the margin of the intrusion; the others are smaller and closer to the border but each appears at the surface over an area of more than 1,000 square feet.

The limestone series presents a monotonous succession of massive and semi-massive blue limestone beds, rather pure above but with much chert in the lower members. The beds are sharply folded with dips usually greater than 45°. Their most common strike is 10° to 20° west of north with dips 50° to 80° westward. Variations both in strike and dip are so numerous and sharp that, though important faults within the limestone area were not recognized, their presence is not improbable.

Fossils found in the upper beds are of upper Mississippian age, indicating that beneath them, unless cut out by the granite intrusion or by faulting, are several thousand feet of limestones, shales and quartzites (corresponding to beds exposed across the valley of Big Lost River) separating them from the Algonkian schists which further separate them, possibly by an equal distance, from the Archean gneiss or its equivalent.

GRANITE PORPHYRY.

Granite porphyry crops out in the western portion of the area represented by the special map, and is a part of a porphyritic intrusion which was mapped over an irregular area of about ten square miles, centering about White Knob. In most places this

formation presents steep slopes which terminate in high peaks, but locally along the margin it is even less resistant to erosion than the adjacent limestone. Thus in the vicinity of the mines the gentle slopes extending back a thousand feet or so from the contact offer some suggestion that the marginal facies is a separate intrusion. Other direct observations, however, make this view entirely untenable.

The normal granite porphyry, as seen in the hand specimen, is a dark gray rock with phenocrysts of feldspar from one quarter to one half inch in length, and rounded crystals of quartz about one quarter of an inch in diameter studding rather thickly a granular groundmass composed of flecks of biotite and needles of hornblende along with important amounts of feldspar. As seen in thin section, orthoclase is the most abundant feldspar, though albite, microcline, and oligoclase, one or all, occur in most of the slides. Quartz, far less abundant than feldspar, exceeds biotite in amount. Hornblende and diopside, though nowhere abundant, vary in amount from place to place. Titanite, magnetite, and apatite are persistent accessories, and rutile is not uncommon. A grain of fluorite was observed in each of two sections. The quartz crystals are more uniformly and extensively embayed than in most of the igneous rocks of east-central Idaho, and locally micropegmatite is exceptionally abundant.

Near the contact the rock in most places is essentially of the same composition as the main body, though here the groundmass is microcrystalline and the feldspar and quartz phenocrysts are much more widely spaced, and are smaller. This facies of the rock merges by imperceptible textural gradations into the normal granite porphyry with which it agrees closely in composition. Contact effects clearly have been caused by both the marginal facies and the normal granite porphyry; the most notable metamorphism by the latter being the transformation of the great mass of blue limestone to white marble on White Knob and its local garnetization, and by the former the development of the garnet shoots in the Empire mine and in the Copper Bullion tunnel.

The width of this marginal zone of finer-textured rock is widely different in different places along the border of the intrusion. In the vicinity of the Empire mine it is 2,000 feet wide, but in the canyon of Cliff Creek it is not more than ten feet in width. It also is narrow where the granite porphyry extends beneath the great marble mountain of White Knob.

DIKE ROCKS.

Three distinct periods of intrusion are represented by the dikes of the district. The oldest dikes are offshoots from the granite porphyry mass. The youngest are similar in mineralogical composition, but contain large phenocrysts, many of which are Carlsbad twins of orthoclase. This rock is designated trachyte porphyry. Aplite dikes are intermediate in age between these two. They were observed only in the vicinity of the Big Quarry and on the ridge northwest of the Copper Bullion tunnel. It is noteworthy that they are entirely fresh below the immediate zone of surface weathering, even in the latter locality where they traverse garnet magnetite rock of granite porphyry derivation. Either the aplite dikes are later than the metamorphism or they represent the channels along which the metamorphosing solutions traveled.

TERTIARY ERUPTIVE ROCKS.

Lavas and tuffs occupy an old erosion valley which crosses the eastern portion of the district and extends off to the south and southeast. The rocks are andesites, latites, rhyolites and related tuffs. In this district no ores occur in them though elsewhere in eastern Idaho the same series encloses gold-silver and locally lead-silver veins.

ECONOMIC GEOLOGY.

THE ORE BODIES.

Distribution.—The ore bodies at Mackay, unlike those of most contact metamorphic replacement deposits, occur within the main igneous mass, well back from its border (Fig. 81). Most of the production has come from shoots of ore situated from 100 to 800 feet out in the granite porphyry, and two carloads were obtained

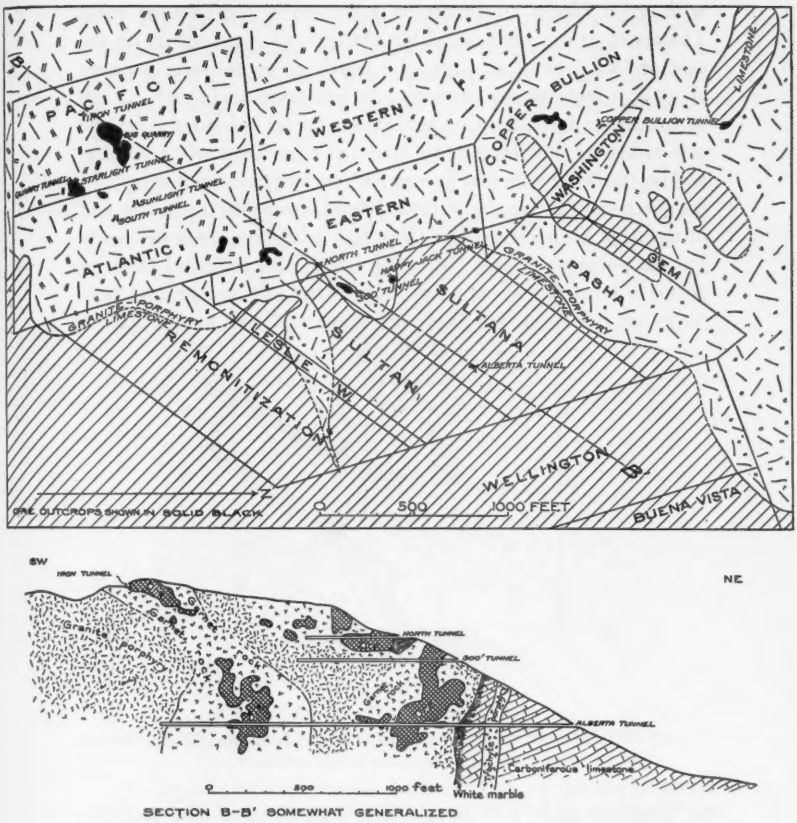

FIG. 81. Geologic map and section of a small area surrounding the Empire Copper Company's principal deposits.

from an ore body situated 1,200 feet back from the main igneous contact. No deposits of proved importance occur in the main limestone area.

The ore bodies however are in several places closely associated

with great blocks of limestone included in the igneous rock. The shoot of ore farthest within the igneous mass occurs on the east end of a block of limestone which crops out over an area about 650 feet east and west by 200 feet north and south. Each of the stopes from the Copper Bullion tunnel is bordered on one side either by limestone or its common equivalent white marble, and on the other either by garnet rock or by granite porphyry. In the north stope above the Alberta tunnel, limestone forms one end of the stope on several floors (Fig. 82) and garnet rock or locally granite porphyry forms the other. The North tunnel near its portal is bordered by white marble on the left and granite porphyry on the right, but beyond a point 205 feet in, the garnet

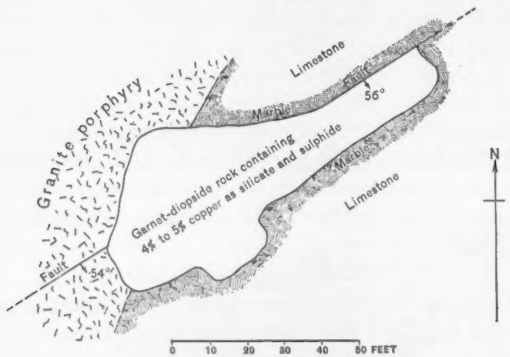

FIG. 82. Plan of a stope on the 450-foot level, north Alberta Shoot. Shows pre-mineral fault sealed by the ore body.

rock appears on both sides. In the south group of stopes above the Alberta tunnel limestone is absent altogether, but even here the garnet rock locally has a faint stratiform appearance which suggests the bedding of limestone not completely metamorphosed.

Garnet rock accompanies all the important ore bodies and in most of the primary ore this mineral is the dominant constituent. The ore shoots are almost invariably bordered on one side, and in many places are completely surrounded, by garnet rock. Section

B–B', Fig. 81, though of necessity generalized in this particular, illustrates the common relation of the shoots of ore to those of garnet rock. Wherever it is possible to make a comparison of the regularity in outline of the ore body and the adjacent mass of garnet rock, the outline of the latter is the more regular.

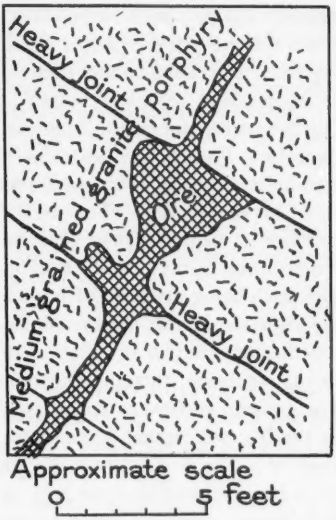

FIG. 83. Detail from south face of Copper Bullion stope No. 2. Shows clearly the replacement of the granite-porphyry after it had solidified.

The apparently heterogeneous distribution of the ore bodies is perhaps the most striking characteristic of these deposits, yet careful observation brings out two very persistent relations: (1) The margins of included limestone blocks are replaced by ore in several places. This is clearly illustrated by all the important stopes in the Copper Bullion tunnel. (2) The ore bodies for 400 feet above the Alberta tunnel are very definitely related to a fault which strikes 20° to 30° to the east of north and dips 50° to 60° to the southeast. The fault may be traced by a pro-

nounced gouge wherever it traverses the granite porphyry, but within the area of garnet rock it is not discernible in many places, and within the ore bodies it is entirely obliterated in the lower stopes in the north end of the mine, though in the south end it shows as a smooth crack accompanied by a little selvage, interpreted as post-mineral movement along a pre-mineral fault. The later fault movement has not been sufficiently great, however, appreciably to offset the ore. In the Copper Bullion tunnel the ore shoots do not appear to be related to any such dominant feature, although details of structure definitely bespeak the influence of joints in directing the movement of the solutions and in shaping the resulting deposits. Figure 83 illustrates the influence of joints here in shaping the ore bodies in granite porphyry.

Characteristics of the Ore Bodies.—The ore bodies vary greatly in size and even more in shape. Three principal groups of ore shoots are recognized, one in the Copper Bullion and two above the Alberta tunnel, each being made up of branching arms which commonly diverge upward but in places unite on higher levels. Most of the ore-bodies are circular or elliptical in plan, and most of them pitch to the southeast, though exceptions are numerous and striking. The greatest vertical extent of an ore body is from a few feet above the No. 300 tunnel down to the 850-foot level. This shoot narrows to a few feet between the 500- and 700-foot levels, but above it has an average floor area of perhaps 3,000 square feet and below of 1,500 or 2,000 square feet. On the 450-foot level it consists of the stope shown in Fig. 82 and a stope 24 feet by 18 feet situated 50 feet in the hanging wall. On the 500-foot level are three stopes, the same one shown in Fig. 82, there somewhat larger, and two chimneys or pipes which lead off into the footwall. One of these is about 7 feet in diameter and the other is 7 by 14 feet in area. The south shoot is similarly irregular in shape and in it the large ore body opened immediately above the tunnel level, splits within a few feet into east and west shoots. The eastern one dies out within a hundred feet, but the western soon splits into four parts, the southernmost one alone continuing to the 300 level. The remark-

able "pipes" or "flues," described by Kemp and Gunther[1] and also by Supt. Ralph Osborn,[2] occur on the ninth floor of the east stope. This stope is no longer accessible but the description by the above writers seems adequate.

"These ('pipes' or 'flues') are surrounded for perhaps a radius of 20 feet at the point exposed, by an intimate mixture of finely-crystalized garnet and specularite, which carries pyrite and chalcopyrite, and their products of oxidation, and fluorite in small but persistent quantity. Through this mass are vugs lined with crystalline garnet, and in several places angular fragments of unaltered quartz-porphyry cemented in the mass, bearing testimony to the fumarolic process.

"The pipes themselves are lined with incrustations of garnet and specularite. Crystalline purple fluorite is present and chalcopyrite occupies the spaces between the other minerals. Additional minerals of probably later origin are siderite incrusting the other minerals, gypsum, which occurs in a similar manner, and calcite, which has come in latest of all, filling the open spaces between the larger crystals and the cracks through the formation.

"These pipes vary in size from those which are now closed, but which exhibit the original structure, to open channels from 8 to 10 inches across."

In the Copper Bullion workings the principal ore bodies as now known are distributed irregularly along the margins of a great limestone inclusion which crops out for 1,000 feet along a northeast course and has an average width of about 200 feet. The Copper Bullion tunnel intersects this limestone slab at a depth of about 200 feet and development has followed its margin for 100 feet above and below the tunnel level and 120 feet to the west and 160 feet to the east. Thus development has been entirely sufficient to afford a reliable conception of the broader geologic relations of the ore bodies here found. Three principal ore shoots are recognized, all of which are bordered on one side by the limestone, or its local equivalent white marble, and on the other by garnet rock or granite porphyry. The stopes are exceedingly irregular on the limestone side; much more so than on the other, as illustrated by Fig. 84. The larger ore bodies are tabular in out-

[1] Kemp J. F., and Gunther, C. G., *op. cit.*, pp. 292–293.
[2] Oral communication.

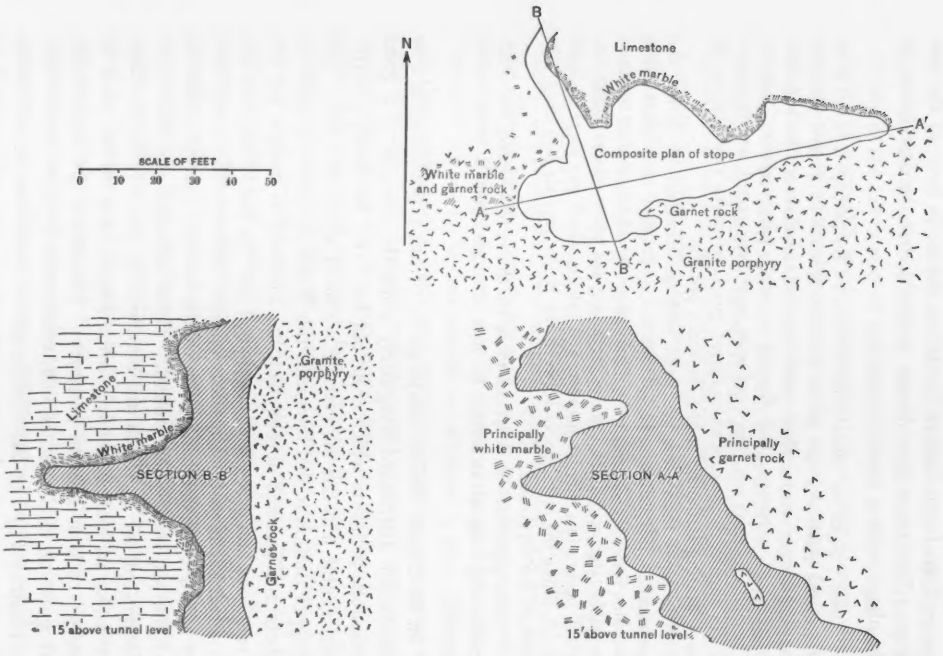

FIG. 84. Plan and sections of Copper Bullion shoot No. 2, which is on the south side of the large limestone inclusion which extends into the Copper Bullion claim from the northeast.

line and parallel to the margins of the limestone slab, but locally chimneys of ore extend off into the limestone or follow up along sharp bends in the limestone-porphyry contact; locally they reach out along joints a short distance into the igneous rock.

Most of the ore has been found on the south side of the inclusion, but to the west of the tunnel important bodies are opened also on the north side. These have been followed by broad flat stopes, which extend through the limestone slab to the south, and connected with other ore bodies west of the tunnel. A similar body of ore, though much smaller, extends into the limestone from the south. A winze about 150 feet deep starts at the tunnel level and bears to the north-northeast, following on a sinuous course this small pipe of ore. Throughout its extent limestone and marble form the roof and garnet rock the floor. This ore body, though not proved to be particularly valuable, seems to represent a pipe extending entirely through the limestone slab.

A body of ore wholly surrounded by the granite porphyry occurs about half way between the limestone inclusion and the portal. This ore is essentially similar to that adjacent to the limestone and it is believed to have had the same origin, the limestone here, however, having been entirely replaced.

Both here and in the Alberta stopes the contact of the ore and the enclosing rock, wherever that is limestone or granite porphyry, is sharp in detail, although in its broader features, even in those of a hand specimen, the contact is exceedingly irregular. Where the enclosing rock is garnet there is a gradation in many places between the ore and the barren formation enclosing it, but even here the transition is nearly complete within a few feet, in most places within a few inches. A striking feature and one found to be most valuable in locating shoots of ore is the presence of stringers which extend out from the ore bodies locally 100 feet or more. This connection of stringers with ore bodies is so general and so well recognized by those acquainted with the deposits that many profitable leases have been taken on seams no wider than a knife blade. The stringers traverse both garnet rock and granite porphyry.

THE ORES.

The ores of the Mackay deposits are valuable for the copper they contain, though small amounts of gold and silver also occur in them. The primary ores comprise an intimate intergrowth of garnet and chalcopyrite along with subordinate amounts of pyroxene, pyrite, and pyrrhotite, the abundance of chalcopyrite being such that the ore contains 5 to 6 per cent. of copper to the ton. The sulphides are characteristically interstitial with respect to the silicate minerals, but in a few of the specimens chalcopyrite and pyrite occur well within garnet crystals. The sulphide ore is known only in the north Alberta shoot and in the Copper Bullion tunnel.

Far more abundant than it is the so-called chrysocolla ore mined at more than thirty places on the Empire group of claims in 1912. These oxidized ores are characteristically a confused assemblage of variegated chrysocolla inclosing numerous blebs and wavy, discontinuous bands of azurite and malachite and locally nodules of cuprite and ill-defined patches of "copper pitch ore." Of the fifty-six mineral species which have been recognized in the deposits, twenty-one occur in these secondary ores.

Although not discussed in this paper it is noteworthy that secondary copper sulphides are exceedingly rare in the deposits and that no zone of sulphide enrichment separates the oxidized and primary ore.

PARAGENESIS OF THE PRIMARY MINERALS.

No rigid sequence in mineral formation has been recognized in the Mackay deposits. In places veinlets of magnetite cut across garnet rock, but elsewhere grains of it are clustered in the centers of fresh garnet crystals. Chalcopyrite locally occurs as veinlets cutting garnet rock and elsewhere bears the same relation to garnet and diopside crystals as does interstitial calcite. The latter is certainly residual, hence the relation may suggest that chalcopyrite has replaced calcite after garnets had ceased to form. Perhaps in the same specimen, however, chalcopyrite occurs zonally distributed well within crystals of garnet. In the Copper

Bullion shoots the persistent occurrence of the ore on the limestone side of garnet masses also suggests that the ore minerals are later than the lime-silicates. It is an unexplained fact that important amounts of chalcopyrite and magnetite have not been found in the same ore body. In the metamorphism of the granite porphyry diopside was the first mineral to form but within limestone areas garnet is euhedral against it. In the former the fact that it replaces hornblende, a mineral of similar molecular structure, may account for its earlier development. Fluorite is common both as veinlets in the lime-silicate rock and as intergrowths with garnet crystals.

In general it is true that magnetite and the sulphides are interstitial with respect to the lime-silicate minerals, and were formed later. Fluorite also is in most places a later mineral.

METAMORPHIC PHENOMENA.

GENERAL STATEMENT.

The metamorphic phenomena at Mackay include the transformation of limestone into marble and garnet rock, and the transformation of the granite porphyry itself into garnet rock. The deposits therefore present both exomorphism and endomorphism. The latter, however, is vastly less extensive than the former and apparently occurs only adjacent to garnet rock of limestone derivation. The deposits are believed to record both metamorphism at the time of intrusion and metasomatism at a subsequent time.

Hydrothermal metamorphism has not been a noteworthy process in the deposits though a little sericite has been recognized in several of the thin sections.

The products of oxidation and hydration in the oxidized zone are particularly interesting because of the preponderance of amorphous constituents, the radial disposition of crystals and the meager transfer of material which they seem to imply. They are not further considered in this paper.

EXOMORPHISM.

Marmorization of the Limestone.—Marble is only developed in important amounts at one place along the several miles of granite porphyry-limestone contact: in most places it is scarcely discernible. Its best development is on White Knob (Fig. 85), a

FIG. 85. Marble mass of White Knob in middle distance as seen from the northeast. The rock formation in the center foreground and along the sides is granite-porphyry.

mountain so named because it stands out as a great white monument on a field of blue, gray and green. It is situated about 3 miles west of the Empire mine. The marble mass is perhaps one square mile in area and rests upon the granite porphyry exposed in four great cirques which head against it. On the northwest side it connects with the main limestone area, showing that the marble represents a portion of the roof of the batholith and not an embayed block. The marble-granite porphyry contact as exposed on three sides of the knob is about 9,500 feet above sea and 1,000 feet lower than the summit, thus indicating that the

marble mass is approximately 1,000 feet thick. The rock, which retains a distinct bedding structure from the original limestone, strikes north-south and dips 80° to 85° to the east. It is possible, therefore, to follow a given bed continuously for about 1,000 feet away from the igneous contact. In this distance no persistent changes in the intensity or character of the metamorphism were recognized. In places the marble is coarse textured, elsewhere fine, some beds are bleached slightly, some still retain the blue of the original limestone but most of them are milky white. None of these differences, however, appear to bear any definite relation to the proximity of the igneous mass. Thin sections of the marble reveal small and rather uniformly distributed crystals of diopside and an occasional one of wollastonite and tremolite in a matrix of calcite which is clear and apparently contains no foreign matter. The silicate minerals seem to be no more abundant next to the igneous contact than elsewhere in the marble mass, except in the form of veins later to be described.

The above relations are interpreted to mean that during the marmorization stage physical-chemical conditions were essentially uniform throughout this great roof segment, which as now exposed is about one square mile in area and 1,000 feet in thickness. The two specimens of adjacent granite-porphyry, which were examined microscopically, show no evidence of hydrothermal metamorphism. Perhaps more noteworthy than this, however, is the absence of similar marmorization along vertical portions of the limestone-granite porphyry contact.

The occurrence of marble about the several blocks of engulfed limestone is more persistent than along the periphery of the batholith, but here also it has a considerable range in width. Four separate blocks of enclosed limestone are represented on the special map. In the mapping the marble was included with the limestone and the garnet rock with the granite porphyry. Marble, however, constitutes only a minor part of most of the areas shown as limestone and in but one place, the large inclusion northwest of the Copper Bullion tunnel, is garnet rock extensively developed. The east one of four inclusions a little north of the area repre-

sented by the special map is composed of chert which, up to the very contact, is apparently unmetamorphosed. The other three areas are of limestone bordered by a zone of marble a few inches or perhaps two feet wide. The large limestone inclusion northwest of the Copper Bullion tunnel is changed to marble for about 100 feet on the southwest side and to garnet rock containing magnetite for 100 feet beyond. On the northeast side of the same engulfed block, however, the marble aureole is only two or three feet wide. The large inclusion of limestone which extends into the Copper Bullion claim shows only a little marmorization at the surface but at a depth of about 200 feet, where the north end of it has been extensively explored from the Copper Bullion tunnel, the marble border is about three feet in average width. In places here the transformation is represented by a zone not more than 1 or 2 inches wide; elsewhere, as in No. 2 stope, there is perhaps 8 feet of marble, 20 feet of ore (garnet, diopside and chalcopyrite or their oxidation products) and 25 feet of garnet rock, between the granite porphyry and the unaltered limestone. In the north ore shoot above the Alberta tunnel, the blue limestone and granite-porphyry were observed in contact with no evidence of metamorphism along the border of either. An excellent exposure of this kind is in the road-cut about 100 feet east of the lower tram station.

The several localities cited above serve to illustrate the peculiarities of distribution of the marble along the contact of the limestone and granite-porphyry, a distribution in no wise related to observed differences in the chemical or physical makeup of either rock. The observations are believed to indicate clearly that the metamorphism is due to something more than a simple heat effect of the newly injected magma upon adjacent rocks. In the following sections other observations are recorded which serve to confirm this belief.

Partial analyses of the unaltered limestone appear on page 329.

Development of Lime-silicate Rock.—The striking and most noteworthy feature of the distribution of the garnet rock is that all the areas are within the main granite-porphyry mass. Three

exceptions only to this generalization were observed. Garnet occurs with magnetite in the Magnetite tunnel of the Champion group (see Fig. 80), with copper ore in the small shaft on the north end of the Remonitization claim, and in three prospects about 500 feet down the east slope of White Knob. The latter occurrence only is worthy of further mention. Here the garnet mass, though poorly exposed, is lenticular in form and cuts across the bedding of the marmorized limestone as a dike or vein.

Of the areas of garnet rock within the granite-porphyry those exposed in the underground workings of the Copper Bullion claim may be most readily studied. Here several hundred feet of development on the ore through a vertical distance of 200 feet clearly shows that a garnet zone borders the west end of the embayed block of limestone which extends into the Copper Bullion claim from the east. A typical section from the center outward here shows blue-gray limestone, white marble, metamorphic silicates and copper minerals intergrown, dense metamorphic silicate rock, and granite-porphyry. In places the outer silicate zone is absent and elsewhere the marble and igneous rock are in contact.

The stopes above the Alberta tunnel, the largest in the district, represent two groups of ore shoots about 600 feet apart and are bordered in most places by garnet rock. In the north set limestone appears in the north end of several floors, but in the south group the surrounding formation is entirely garnet rock and granite-porphyry. Here, however, much of the silicate rock contains interstitial calcite similar in every respect to that found in garnet and diopside rock which is unquestionably of limestone derivation. Here also much of the silicate rock has a faint stratiform structure, due to slight differences in the relative abundance of garnet and diopside and to the size of the crystal grains, believed to indicate bedding retained from replaced limestone.

The two principal groups of garnet shoots in the Alberta workings are clearly related to the fault described on page 315. This fault shows clearly in crosscuts nos. 2, 4, 6 and 7 from the Alberta tunnel (Fig. 86), at several places in the south group of

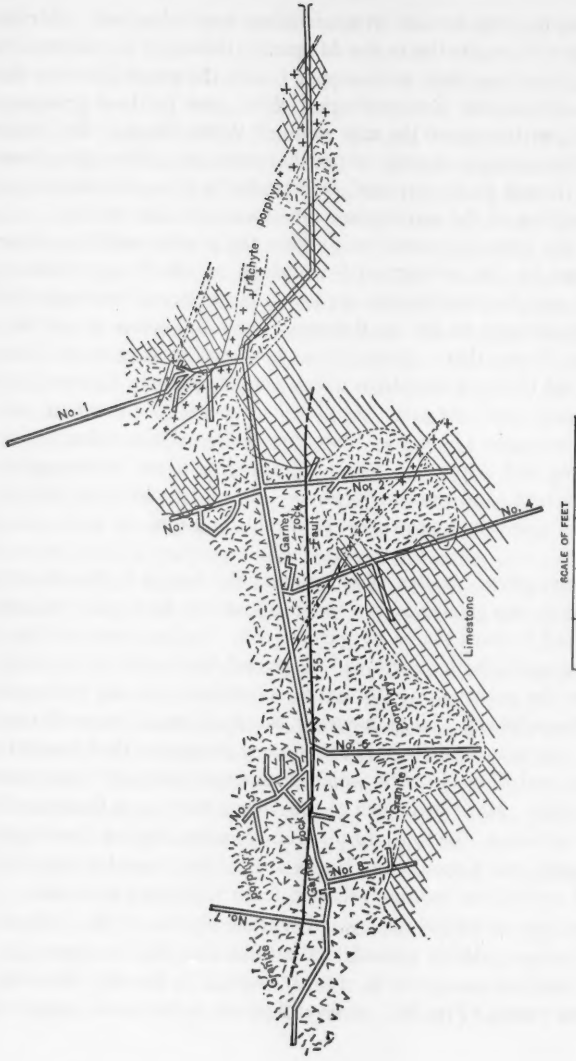

FIG. 86. Geologic map of Alberta level, Empire mine.

stopes, and locally in the walls of the north stopes. It also is followed for about 600 feet by the 300-foot tunnel at a level 400 feet above the Alberta tunnel. In the North tunnel, 117 feet above the 300, it is only recognized in the last west crosscut, the tunnel being driven in its hanging wall. The fault-plane is characterized by a gouge and crushed zone from a few inches to several feet wide wherever it crosses the granite-porphyry or the limestone, but within the ore or the lime silicate rock it is nowhere conspicuous.

The above relations are interpreted to mean that the localization of garnet shoots in the Alberta workings is due both to the influence of included blocks of limestone now completely transformed and to the presence of what for convenience may be called the Alberta fault.

Discussion of Analyses.

Analyses have been made both of the limestone and the secondary silicate rock resulting from it, in order to see what changes accompanied the metamorphism. As is discussed in another section (p. 344) volume changes during the transformation are negligible. It is necessary, therefore, in the following discussion to know the density of the rock types and the percentage of constituents in them in order to determine gains and losses. The percentage of any constituent multiplied by the density of the rock gives the number of grams of that constituent in a cubic centimeter. Thus the number of grams of the several constituents in the original and in the derived rocks affords an easy basis for comparison. In the following tables and figures this number is multiplied by 100 to bring the volume to a scale convenient for plotting and to reduce the significance of fractions. The method here used for plotting the gains and losses has (Figs. 87 and 89) the advantage over diagrams commonly used in that areas are proportional to each other, difference in density is shown to scale, and a progressive change involving several analyses may be represented.

Analyses of the fresh limestone and products resulting from

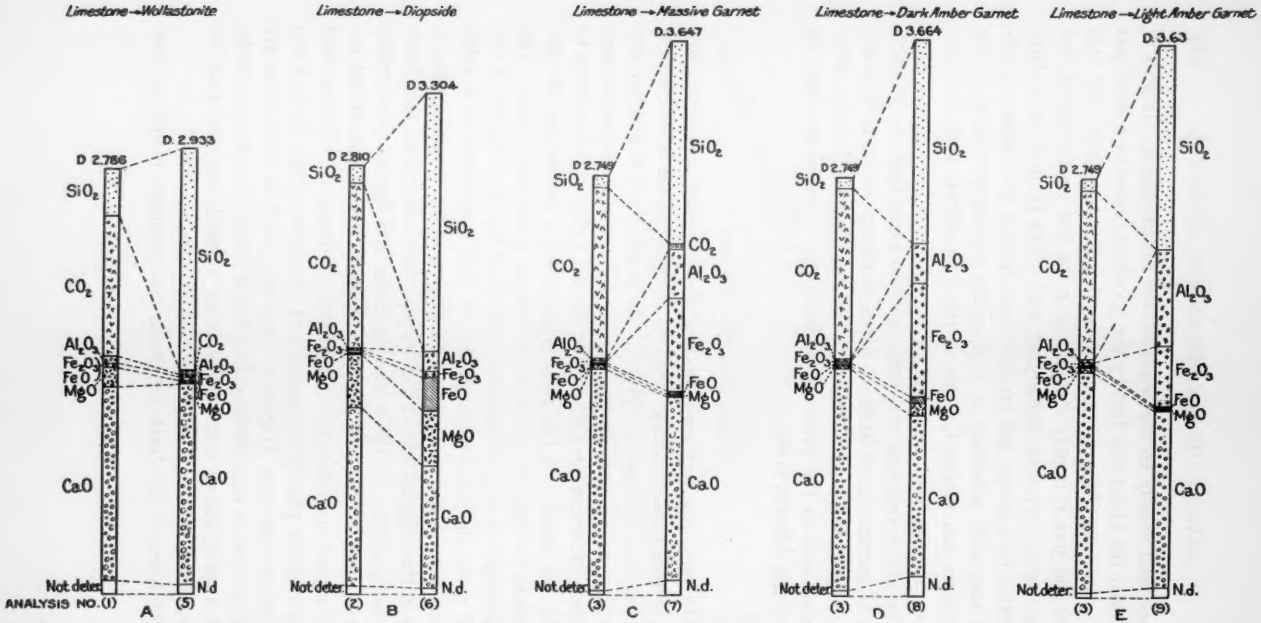

FIG. 87. Diagrams showing gain or less of each constituent in grams in the transformation of 100 cubic centimeters of limestone to the same volume of secondary silicate rock. Scale 1 inch equals 100 grams.

ANALYSES OF LIMESTONE AND SILICATE ROCKS RESULTING FROM IT.

	1	2	3	4	5	6	7	8	9	Gain or Loss in Grams per 100 c.c.				
										1→5	2→6	3→7	3→8	3→9
SiO_2	11.02	3.92	2.84	1.67	50.47	51.55	36.92	36.57	37.07	+117.14	+159.10	+126.96	+126.04	+126.75
Al_2O_3	.90	.72	.18	.30	.45	4.00	8.75	7.56	17.42	− 1.19	+ 11.18	+ 31.44	+ 27.17	+ 62.73
Fe_2O_3	.24	.04	.13	.16	.16	1.02	16.85	20.34	10.81	− .19	+ 3.25	+ 61.14	+ 74.08	+ 38.88
FeO	.08	.26	.09	.08	.10	6.65	.50	1.24	.68	+ .07	+ 21.21	+ 1.55	+ 4.27	+ 2.20
MgO	4.73	12.72	1.03	.48	1.17	11.38	.17	2.10	.51	− 9.78	+ 1.81	− 2.21	+ 4.85	− 1.02
CaO	47.39	42.14	54.14	53.71	45.99	24.23	33.71	30.20	32.77	+ 2.54	− 38.45	− 25.84	− 38.35	− 29.92
Na_2O	.....	.....	.....	.....	.....	.38	.31	.....	.....	.....	.....	.....	.....	.....
K_2O	.....	.....	.....	.....	.....	.18	.21	.....	.....	.....	.....	.....	.....	.....
H_2O-	.....	.....	.....	.....	.....	.14	.21	.30	.....	.....	.....	.....	.....	.....
H_2O+	.....	.....	.....	.....	.....	.25	.39	.54	.14	.....	.....	.....	.....	.....
TiO_2	.....	.....	.....	.....	.....	.32	.26	.20	.39	.....	.....	.....	.....	.....
CO_2	33.71	38.98	41.28	41.89	.69	.0	.95	.0	.....	− 92.00	−109.53	−110.05	−113.52	−113.52
P_2O_5	.....	.....	.....	.....	.....	.24	.30	.23	.....	.....	.....	.....	.....	.....
MnO	.....	.....	.....	.....	.....	.30	.67	.60	.....	.....	.....	.....	.....	.....
Totals	98.07	98.78	99.69	98.29	99.03	100.64	100.20	99.88	99.79	+ 16.59	+ 48.57	+ 82.98	+ 84.54	+ 86.10
Sp. gr. (lump)	2.786	2.810	2.749	2.728	2.933	3.304	3.647	3.664	3.63*					

1. Limestone, Cave tunnel, Champion group. W. C. Wheeler, analyst.
2. Limestone, first bend from portal in Alberta tunnel. W. C. Wheeler, analyst.
3. Limestone, near first right lateral No. 4 crosscut, Alberta tunnel. W. C. Wheeler, analyst.
4. Limestone, near first lateral No. 3 crosscut, Alberta tunnel. W. C. Wheeler, analyst.
5. Wollastonite rock opposite side of same hand specimen as No. 1. W. C. Wheeler, analyst.
6. Diopside rock near second lateral No. 3 crosscut, Alberta tunnel. Chase Palmer, analyst.
7. Massive garnet rock 100 ft. S. of No. 5 crosscut, Alberta tunnel. Chase Palmer, analyst.
8. Dark amber-colored garnet crystals, 1500 ft. NW. of Copper Bullion tunnel. Chase Palmer, analyst.
9. Light amber-colored garnet crystals, Kemp and Gunther, *op. cit.*, p. 318. Cyril Knight, analyst.

* Density computed from the analysis.

it are shown below and are accompanied by diagrams illustrating the gain or loss of each constituent.

Many more combinations of the analyses are possible than are shown by the diagrams (Fig. 87) but these are believed to be the most reasonable. It is possible, however, to re-combine the columns mentally as all are plotted on the same scale. In the development of wollastonite from limestone the substitution of silica for carbon dioxide alone is important. In the formation of diopside from a magnesium limestone the same substitution is important; but alumina and ferrous iron are added and calcium oxide partly extracted. The development of the several types of garnet implies a great addition of silica, alumina, and ferric iron along with a noteworthy loss of calcium oxide and the almost complete elimination of carbon dioxide. The different garnet types depend upon the relative amounts of ferric iron and alumina added.

The most important fact brought out by the analyses, however, is the tremendous amounts of silica, alumina and iron which have been added to the contact zone during metamorphism. Under another heading (p. 349) relations are considered which lead to the conclusion that the magma supplied this material.

ENDOMORPHISM.

The granite-porphyry itself is completely transformed into garnet rock in many places, the localization of it being even more erratic than that of limestone derivation. In general, it seems true that the former only occurs adjacent to the latter, but many places were observed where the limestone had been intensely metamorphosed without the igneous rock having been affected. Where the silicate rock is bordered by granite-porphyry the contact is locally much more irregular in detail than where bordered by marble, though more regular in general outline. In many places stringers of garnet-diopside-chalcopyrite rock have been followed out along joints 10 to 20 or even 100 feet into the granite-porphyry. In places, at the intersection of cross joints these open out into bunches of ore of minable size. The transi-

tion from silicate rock to granite-porphyry in such situations is locally complete within a few millimeters, but elsewhere the transition zone is two or three feet wide. Adjacent to the contact

A

B

FIG. 88. *A*. Garnetized granite-porphyry from near the Iron tunnel. Shows garnetization progressing inward from joints along the lower and left sides. The dark band along the contact of garnet and porphyry is due to a depression developed during polishing. Actual size. *B*. Garnetized granite-porphyry from 100 feet in, on crosscut No. 6, Alberta tunnel. The dark area is principally garnet, cut by veinlets of fluorite (white); the large light area is diopsidized granite-porphyry. Actual size. For description see page 332.

Fig. 82) great bodies of ore cut sharply across the contact. Fig. 88 illustrates the occasional sharp transition from garnet rock into the granite-porphyry which it replaces. Five thin sections were cut from the larger specimen, three across the contact and one near the outer edge on each side. The section of the granite-porphyry contains orthoclase, albite, microcline and oligoclase, together with remnants of biotite and hornblende, as the essential original minerals. Diopside in small diversely oriented secondary diopside is abundantly developed in the igneous rock; nearby after all the original minerals, farther away only after the biotite and hornblende, the latter being replaced first. Fig. 83 illustrates a common relation of garnetiferous ore to the granite porphyry in the Copper Bullion workings. It also shows the influence of joints in determining points of maximum replacement.

Along the Alberta fault the igneous rock has been transformed into garnet-diopside rock in many places. Here also the metamorphic silicates in places clearly follow joints in coarse-textured granite-porphyry. Elsewhere kidney-like protuberances of the silicate minerals extend into the igneous mass and again (as in crystals is abundant after the hornblende and biotite, in most places completely replacing the former and leaving only small cores of the latter. The feldspar phenocrysts are commonly fresh though diopside replaces some of the oligoclase. Throughout the groundmass finely divided diopside is uniformly present. No garnet was recognized but it is possible that augite occurs. The slide from the opposite edge of the specimen is made up of garnet, diopside, a little tremolite, and even less fluorite. The diopside occurs principally as minute grains, some of which are so grouped as to suggest the shape of a basal section of hornblende and others suggest the outlines of biotite. Though garnet is here the most abundant mineral, a great deal of finely divided diopside is scattered through it. The tremolite, and possibly also some wollastonite, is mostly intergrown with the diopside, but it locally occurs in little veinlets crossing the other minerals. Fluorite is confined to veinlets. The three slides which cross the contact show on opposite ends conditions similar to those de-

scribed above. The immediate line of contact is marked by a wavy band of dense garnet which grades back into garnet rock in which crystal outlines are more readily recognized. In one place a feldspar phenocryst is truncated by the garnet, the continuation of the feldspar in the garnet being marked by finely divided diopside.

The order of replacement during endomorphism seems to be hornblende, biotite, quartz, plagioclase, orthoclase, phenocrysts of the last two remaining until the groundmass is almost completely changed. The order of formation of the replacing minerals is diopside, garnet, tremolite, fluorite. In no place do large ore bodies occur in garnet-diopside rock clearly of granite-porphyry derivation, though due to the difficulty in distinguishing such rock in most places, but little weight should be given to the observation.

ANALYSES OF FRESH AND ALTERED GRANITE-PORPHYRY AND MASSIVE GARNET ROCK. CHASE PALMER, ANALYST.

	Analyses.			Gain or Loss in Grams per 100 c.c.		
	10	11	7	10→11	10→7	11→7
SiO_2	71.26	70.18	36.92	−2.64	− 52.13	− 49.49
Al_2O_3	13.94	12.97	8.75	−2.35	− 4.53	− 2.18
Fe_2O_3	1.01	.82	16.85	− .49	+ 59.40	+ 59.89
FeO	1.35	.86	.50	−1.28	− 1.72	− .44
MgO	.67	.95	.17	+ .74	− 1.14	− 1.88
CaO	1.64	3.98	33.71	+6.18	+119.83	+113.65
Na_2O	3.96	2.89	.31	−2.83	− 9.30	− 6.47
K_2O	4.35	5.40	.21	+2.78	− 10.74	− 13.52
H_2O-	.26	.18	.21	− .21	+ .05	− .27
H_2O+	.55	.29	.39	− .69	− .01	− .68
TiO_2	.56	.54	.26	− .05	− .52	− .49
P_2O_5	.10	.26	.30	+ .42	+ .84	+ .42
F	.018	.035	——	+ .05	——	——
MnO	.55	.55	.67	+ .01	+ 1.02	+ 1.03
CO_2			.95		+ 3.49	+ 3.49
	100.22	99.91	100.20	+ .36	+104.53	+104.17
Sp. gr.	2.637	2.64	3.683			

10. Fresh granite-porphyry, 400 feet NE. of Mineral Monument No. 1.

11. Diopsidized granite-porphyry near mouth second lateral No. 4 crosscut, Alberta tunnel.

7. Massive garnet, Alberta tunnel, 100 feet south of No. 5 crosscut. Same as analysis No. 7, p. 329.

Discussion of Analyses.

The transition from diopsidized granite-porphyry into garnet rock is very abrupt as shown by two hand specimens illustrated in Fig. 88. From fresh granite-porphyry to that containing large amounts of secondary diopside the transition zone extends over

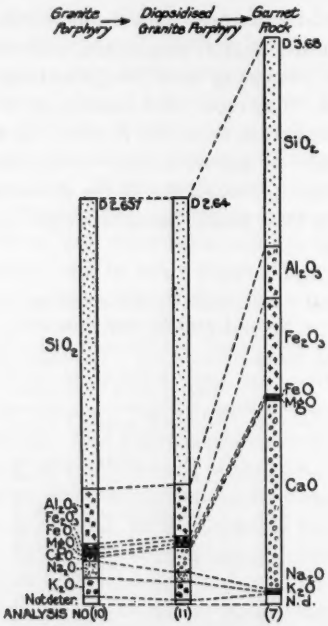

FIG. 89. Diagram showing gain or loss of each constituent in grams in the transformation of 100 cubic centimeters of granite-porphyry to the same volume of diopsidized granite-porphyry and this to massive garnet rock. Scale 1 inch equals 100 grams.

many feet. The specimen of altered granite-porphyry which was analyzed is believed to represent nearly the maximum development of diopside prior to the initiation of garnet replacement. The specimen of garnet rock here presented is probably of lime-

stone derivation but, as in the hand specimen and in the thin section it is impossible to distinguish it from other specimens clearly of granite-porphyry derivation, a separate analysis was not believed to be warranted. The analysis of granite-porphyry represents a perfectly fresh rock. Here again the computations are based on constant volumes.

It is particularly striking (Fig. 89) that in the diopsidization of the granite-porphyry the only important addition is calcium oxide which in part seems to replace soda. In the further transition to massive garnet, however, there are notable additions of both lime and ferric iron accompanied by a proportionally much smaller loss of silica, soda, and potash. Throughout the transformation, alumina, ferrous iron and magnesia remain essentially constant. The principal difference between the development of garnet from granite-porphyry, as above, and from limestone, previously described, is that here lime has been added in large amounts and silica subtracted, and there silica has been largely added and lime remained constant or was reduced. This metamorphism requires primarily a supply of lime and iron; that a supply of silica, alumina and iron. These in part compensating requirements would seem to favor the metamorphism of both the igneous and calcareous rocks where they are adjacent.

RELATIVE IMPORTANCE OF ENDOMORPHISM AND EXOMORPHISM.

Satisfactory criteria for distinguishing the products of endomorphism from those of exomorphism in these deposits have not been recognized. Apatite has not been found in the silicate rock unquestionably of limestone derivation, whereas it does occur in that replacing the granite-porphyry. Titanite is likewise confined to the latter so far as observed. Both of these minerals, however, are common in contact metamorphic deposits and to rely on them as definite criteria would be to invite the probability of an erroneous conclusion. Locally the lime silicate rock retains in part the pattern of the igneous rock and elsewhere it shows the bedding structure of the limestone, but such features were recognized only in the border phases of the metamorphism. In

many places the metamorphic silicates are set in an abundant matrix of calcite, but this is common only near a marble contact where the derivation from limestone is otherwise apparent. All of these features fail or become unreliable in the wide zones of most intense metamorphism, many of which have on the one side garnet rock clearly developed from limestone, and on the other that developed from granite-porphyry. Broad relations only can be resorted to in determining the relative importance of the exomorphism and endomorphism, but these point to the former as being much the more important quantitatively. Where bodies of silicate rock cross the contact as in Fig. 82, they invariably attain their maximum development in the limestone; also the number of places where the ore bodies are near limestone is far greater than the number where they are close to the porphyry. The general fact that endomorphism of this sort is uncommon as compared with similar exomorphism argues further, though probably weakly, for the same conclusion. Another line of attack is a determination of the amount of calcium oxide available for exomorphism after endomorphism is complete. This may be easily calculated, as volumes remained essentially constant during metamorphism (p. 344). Such calculations, in which are used extreme values for specific gravities and composition, show that not more than 20 per cent. of the lime in the original block was expelled and thus was available for the development of garnet and diopside in the adjacent igneous rock. Thus if there was no escape of lime and no supply from the rising solutions, not over 20 per cent. of the garnet rock is of granite-porphyry derivation; likely 10 per cent. is a fair average.

HYDROTHERMAL METAMORPHISM.

The products of normal hydrothermal metamorphism are meager in these deposits. Sericite is present in many of the specimens of the granite-porphyry from near the surface but is completely lacking in those taken at a depth of a few hundred feet. Chlorite similarly is confined to the surface rocks. In this particular the deposits are very different from those at

Clifton-Morenci,[1] and Silverbell,[2] though similar to those at Dolores,[3] and San Jose.[4]

MINERALS DEVELOPED DURING IGNEOUS METAMORPHISM.

A complete description of the mineralogy of the district is not attempted here, but some of the minerals particularly related to the igneous metamorphism will be discussed.

Garnet represents perhaps 85 per cent. of the intensely metamorphosed rock. The common variety makes up a massive, often aphanitic rock of peculiar greasy luster. It commonly contains minute veinlets and interstitial areas of calcite, and under the microscope this mineral together with diopside, wollastonite and quartz are seen to be the common accessory minerals; apatite and titanite have been detected in a few sections. Locally the garnet occurs as distinct crystals. Most of these agree in color with the massive garnet rock but some are distinctly lighter and others are much darker. The lighter variety appears to be characteristic of the margins of metamorphic areas but the dark one is commonly in association with magnetite as veinlets in many places cutting other garnet rock. Thin sections of the former, which in most places are imbedded in calcite, show a clear garnet commonly without a pronounced zonal growth and containing but few inclusions. The later, darker garnet in many places contains irregular cores of magnetite and zonal growth appears to be characteristic of them. Four analyses are available, two of which appear in the paper by Kemp and Gunther. Two of the analyses are of the massive garnet, one is of the dark amber-colored garnet of later development, and the other is described by Kemp and Gunther as "light amber-colored garnet." This is believed to represent the light-colored garnet crystals imbedded in the calcite about the margins of massive garnet areas.

[1] Prof. Paper No. 43, U. S. Geol. Survey, 1905, p. 110.
[2] Bull. No. 65, Am. Inst. Min Eng., 1912, pp. 480–481.
[3] Econ. Geol., Vol. 7, No. 5, 1912, p. 481.
[4] Bi-Monthly Bull. No. 4, Am. Inst. Min. Eng., 1905, p. 901.

COMPOSITION OF GARNET ROCK.

Analyses.					Approximate Quantity of Minerals.				
	7	12	8	9		7a	12a	8a	9a
SiO_2	36.92	37.79	36.57	37.07	Grossularite..... ($3CaO, Al_2O_3, 3SiO_2$)	35.55	47.82	23.51	69.26
Al_2O_3	8.75	11.97	7.56	17.42					
Fe_2O_3	16.85	15.77	20.34	10.81					
FeO	.50	1.31	1.24	.68	Andradite..... ($3CaO, Fe_2O_3, 3SiO_2$)	53.49	44.16	60.64	21.13
MgO	.17	.37	2.10	.51					
CaO	33.71	32.57	30.20	32.77					
Na_2O	.31				Almandite..... ($3FeO, Al_2O_3, 3SiO_2$)	1.15	2.99	2.61	1.61
K_2O	.21								
$H_2O -$	.21	.09	.30	.14					
$H_2O +$	.39	—	.54	.39	Pyrope..... ($3MgO, Al_2O_3, 3SiO_2$)	.56	1.31	9.21	1.44
TiO_2	.26		.20						
CO_2	.95		—						
P_2O_5	.30		.23		Spessarite..... ($3MnO, Al_2O_3, 3SiO_2$)	1.53	.68	1.29	—
MnO	.67	.31	.60	—					
	100.20	100.18	99.88	99.79	Wollastonite.....	4.20	—	.94	—
					Hematite.....	—	1.90	—	4.25
					Quartz.....	.26	1.32	.26	—
					Calcite.....	2.16	—	—	2.62
					Apatite.....	.54	—	.50	—
					Titanite.....	.33	—	.50	—
						99.77	100.18	99.46	100.31

7. Normal massive garnet, Alberta tunnel, 100 feet south of No. 5 crosscut. Chase Palmer, analyst.

12. Massive garnet, Kemp & Gunther, *op. cit.*, p. 318. T. T. Read, analyst.

8. Dark amber-colored garnet, distinct crystals, 1,500 feet northwest of Copper Bullion tunnel. Chase Palmer, analyst.

9. Light amber-colored garnet, Kemp & Gunther, *op. cit.*, p. 318. Cyril Knight, analyst.

Each of the garnet analyses above are recast in order to further emphasize the observation of Kemp and Gunther that the andradite molecule is important in all the forms found in the Mackay deposits. It would seem that in the massive garnet andradite is even more abundant than grossularite. Andradite comprises 60 per cent. of the dark amber-colored crystals but only 21 per cent. of the light amber-colored crystals, suggesting that in these deposits color is a fair criterion for determining the approximate type of garnet. Andradite is of particular interest in contact deposits because of the large amount of iron which it contains.

Pyroxene is second to garnet among the contact metamorphic

minerals of the deposits. It occurs in the garnet rock, as small disseminated crystals in the marble, after hornblende and biotite in the endomorphosed granite-porphyry, and as a dense aphanitic rock of green color; locally as a white, marble-like rock composed almost entirely of wollastonite. Analysis was made of both the dark and the light-colored massive pyroxene rock and with the former is presented one published by Kemp and Gunther.

COMPOSITION OF DARK-COLORED PYROXENE ROCK.
W. C. Wheeler, Analyst.

Analyses.			Approximate Quantity of Minerals.			
	6	13		6a	13a	
SiO_2	51.55	45.85	Pyroxene:			
Al_2O_3	4.00	12.21	CaO, SiO_2	37.91	54.98	diopside
Fe_2O_3	1.02	2.15	MgO, SiO_2	24.84	8.70	diopside
FeO	6.65	2.49	FeO, SiO_2	12.30	4.62	
MgO	11.38	8.70	CaO, SiO_2	11.28	4.06	hedenbergite
CaO	24.23	28.54	MnO, SiO_2	.52	——	hedenbergite
Na_2O	.38		MgO, Al_2O_3, SiO_2	7.91	24.04	
K_2O	.18		MgO, Fe_2O_3, SiO_2	—	3.38	augite
H_2O-	.14		Na_2O, Fe_2O_3, SiO_2	1.69	——	augite
H_2O+	.25		K_2O, Al_2O_3, SiO_2	.51	——	augite
TiO_2	.32		Apatite	.49		
CO_2	.00		Titanite	.78		
P_2O_5	.24		Water	1.26		
MnO	.30		Quartz	1.09		
	100.64	99.94		100.58	99.78	

6. Massive pyroxene rock, near second lateral No. 3 crosscut, Alberta tunnel. Chase Palmer, analyst.
13. "Diopside rock," Kemp and Gunther, *op. cit.*, p. 320. T. T. Read, analyst.

Thin sections of the above material reveal diopside and very rarely hedenbergite and augite, but no wollastonite. In recasting the analyses into approximate quantity of minerals, therefore, no allowance has been made for the pure lime-silicate pyroxene. It is noteworthy that considerable iron and alumina are here represented although the amount is far less than in the garnet.

The white pyroxene rock was powdered and examined in index solutions in order to determine what minerals should be recognized in recasting the analysis. Wollastonite is the essential mineral but diopside, augite, calcite and quartz may be identified.

Hedenbergite is assumed to be present because of the ferrous iron. In the formation of this rock from the limestone it is necessary to introduce much silica but essentially no iron or alumina.

COMPOSITION OF WHITE PYROXENE ROCK.

Analysis.		Approximate Quantity of Minerals.	
	(5)		(5a)
SiO_2	50.47	Pyroxene:	
Al_2O_3	.45	CaO, SiO_2	91.24 wollastonite
Fe_2O_3	.16	MgO, SiO_2 }	5.61 diopside
FeO	.10	CaO, SiO_2 }	
MgO	1.17	FeO, SiO_2 }	.23 hedenbergite
CaO	45.99	CaO, SiO_2 }	
CO_2	.69	MgO, Al_2O_3, SiO_2 }	.89 augite
		MgO, Fe_2O_3, SiO_2 }	
	99.03	Calcite	1.75
		Quartz	.28
			100.00

5. Massive wollastonite resembling the fine-grained white marble. From Cave tunnel, Champion Group.

From the foregoing discussion and also from the diagram, Fig. 87, it appears that the light pyroxene or wollastonite rock requires an important addition of silica. The dark pyroxene or diopside rock requires a large addition of silica and noteworthy amounts of both iron and alumina. In the garnet rock, however, additions are most important and here silica, alumina and iron are all added in large amounts. As garnet is the predominant mineral in the deposits the additions which it implies should be considered typical of the Mackay contact zones.

TWO STAGES OF METAMORPHISM.

It is believed that two distinct stages of metamorphism are recorded in the Mackay deposits. These may be distinguished as contact metamorphism at the time of intrusion, and contact metasomatism subsequently. That the development of the lime silicate rock took place in the main after the solidification of the outer few hundred feet of the batholith is perfectly clear. It is fairly certain also that most of the marmorization occurred at an earlier

time. Whether or not there was a distinct break between the two stages, however, is not definitely determinable from available evidence.

The great marble mass of White Knob as already suggested (page 323) affords evidence that at the time of its marmorization physical-chemical conditions were essentially uniform throughout its mass. There is absolutely no evidence that the metamorphosing solutions were fed to it from local vents in the granite-porphyry but rather the evidence indicates that the supply of heat and vapor was the same at all parts of its contact with the igneous rock. It is believed that vapors rising from the entire upper surface of the intrusion caused the transformation. This conception, however, is very different from that thought to account for the garnet dike which traverses the marble beds on the east slope of the Knob. Here the escaping solutions were supplied locally, along a nearly vertical fissure, and although they worked upward for 300 or 400 feet, changing the marble to garnet-magnetite rock, they did not work laterally more than a few feet. It is also worthy of note that vertical portions of the limestone-granite-porphyry contact are not marmorized for more than a few inches whereas the great segment of the roof represented by White Knob is transformed to marble throughout its entire thickness of 1,000 feet over an area of about one square mile.

Blocks of limestone engulfed in the magma show a rather persistent marble border which ranges in width from perhaps 2 feet to 100 or more; locally it is absent. This general distribution of marble though erratic is far more regular than that of the lime-silicate rock, as shown in the following paragraphs.

The distribution of the garnet rock is exceedingly erratic but in many places its localization is clearly due to faults and joints in the granite-porphyry, as in the Alberta and Copper Bullion tunnels. In the latter locality ore replaces the igneous rock along joints opening out locally into minable bodies at the intersection of cross joints (Fig. 83). In the Alberta tunnel a distinct fault has unquestionably directed the ore-bearing solutions. That the

metamorphism was later than the solidification of at least the outer part of the magma is also proven by hand specimens which show garnet replacing the igneous rock from joints and along irregular surfaces. One specimen in the collection (Fig. 88 B, described on page 332) came from No. 6 crosscut of the Alberta tunnel at a point 700 feet below the surface and at least 200 feet from the periphery of the batholith. Another specimen (Fig. 88, *A*) taken near the Iron tunnel came from 1,000 feet within the granite-porphyry area, although here record of the vertical distance to the roof of the batholith is obliterated by erosion.

From the above observations it is certain that the garnet-forming solutions, at least in major part, escaped after the solidification and fracturing of the outer part of the batholith. That marmorization accompanied the intrusion, on the other hand, is believed to be proved by the uniform metamorphism of White Knob. Furthermore, the general persistence of marble about the periphery of included blocks favors this belief. The development of marble, however, was not merely a heat effect for it is noticeable that vertical portions of the contact are not affected as extensively as where the limestone overlaps the igneous rock. Heat probably was conducted almost equally in all directions, but vapors would tend to escape upward both by reason of their low density and because the fracturing of the roof incident to intrusion would determine lines of easy passage toward the surface. These solutions are conceived to have been principally water vapor, for no evidence of accessions of material have been noted in connection with this earlier metamorphism. The sparse and minute crystals of diopside, tremolite and wollastonite in the marble of White Knob are believed to represent merely impurities in the original limestone.

In conclusion it is believed that two types of solutions escaped from the magma—the one before and during the consolidation of an outer shell, and the other after its consolidation and fracturing. It is believed that the earlier solutions caused only a recrystallization of the limestone whereas the later solutions transformed much of the limestone into lime-silicate rock. The

earlier were characterized by water vapor; the later by silica, alumina, iron, fluorine, etc., in addition to water vapor. Whether or not the earlier solutions graded into the later ones and thus the two represent end stages in a continuous period of magmatic emanation is not susceptible of rigorous proof. It is the opinion of the writer, however, that two separate and distinct stages of magmatic emanation are represented and this concept has led to an attempt to formulate an hypothesis to account for the relations illustrated in the Mackay deposits (p. 354).

INTERPRETATION AND CONCLUSIONS.

The more vital questions confronting the student of contact metamorphic replacement deposits at present are: (1) Do the lime silicates and ore minerals represent in large part contributions from the magma, or are they to be accounted for by a concentration of impurities in the original limestone; (2) does the metamorphism occur at the time of intrusion or subsequently; (3) in a given deposit are there successive waves of metamorphism; (4) in general is there a progressive change in the composition of the metamorphosing solutions; (5) is it possible to account for the contact rocks by a stimulation of meteoric circulation along the contact at the time of magma injection and during its period of cooling? These and many other problems confront the student of contact metamorphic deposits. Apparently no two deposits of this type have had precisely the same history, but they all have so much in common that the evidence from local occurrences is of paramount value in testing general hypotheses.

The evidence afforded by the Mackay deposits will be assembled with respect to the several problems above enumerated. Because of their interrelation, however, they can not well be taken up in the order of their importance, but rather in the order of cumulative evidence.

RÔLE OF MAGMA IN SUPPLYING MATERIAL TO THE CONTACT ZONE.

Absence of Volume Changes during Metamorphism.—A striking feature of the Mackay deposits is the definite relation of many of the ore bodies and presumably all of them to blocks of limestone engulfed in the granite-porphyry magma. The several miles of contact along the periphery of the batholith though fairly well prospected have revealed no ore deposits of value and in only two or three places have contact silicates been found;

PARTIAL ANALYSES OF UNALTERED LIMESTONE FROM THE ALBERTA LEVEL OF THE EMPIRE MINE.

	2	4	3	14*
SiO_2	3.92	1.67	2.84	14.77
Al_2O_3	.72	.30	.18	3.68
Fe_2O_3	.04	.16	.13	
FeO	.26	.08	.09	
MgO	12.72	.48	1.03	4.23
CaO	42.14	53.71	54.14	40.62
CO_2	38.98	41.89	41.28	36.58
Loss on ignition less CO_2	.47	.49	.41	
	99.25	98.78	100.10	99.88
Sp. gr. (lump)	2.810	2.728	2.749	
Sp. gr. (powder)	2.816	2.729	2.749	

2. From first bend in Alberta tunnel.
4. From near first lateral from No. 3 crosscut, Alberta tunnel.
3. From No. 4 crosscut near first right lateral, Alberta tunnel.
4. From Alberta tunnel 50 feet from portal.
* Analysis from paper by Kemp and Gunther, *op. cit.*, p. 308. Partly recalculated to show separately CaO, MgO and CO_2.

the ore occurs entirely within the area of the batholith. If therefore the ore and lime silicate rock are due to the concentration of impurities within the limestone, the concentration has taken place entirely within the boundary of engulfed blocks. Some of these have been completely transformed into lime silicates and metallic minerals; others are partly preserved. The approximate composition of the blocks at present and of the original limestone being known, it is therefore possible to compute, roughly to be sure, the volume changes that must have taken place if these

minerals are due to a concentration of impurities already in the limestone.

Four analyses of the unaltered blue-gray limestone are available, one by Professor Kemp and three by W. C. Wheeler, of the Geological Survey laboratory.

The analyses show a considerable range in the composition of the limestone but as the material represents stratigraphic horizons perhaps 200 feet apart, the accordance in composition would seem to be fully as noteworthy as the variation. The alumina and iron are uniformly low, and in only one analysis is the silica high. The analyses therefore are adequate for purposes of emphasizing the order of concentration necessary if we assume that the silica, iron and alumina of the silicate rock represent merely a concentration of elements already in the limestone. In order to derive the silica of the massive garnet rock (No. 7 in Table), from limestone No. 4 there must be a decrease in volume of about 95 per cent.; to derive it from No. 14, which is exceptionally high in silica, a decrease of about 60 per cent. In order to concentrate alumina and iron, the two other significant elements, a concentration of more than 90 per cent. is required for each of the three limestones in which alumina and iron have been separately determined. From these figures, only presented to emphasize an order of magnitude, it is safe to conclude that unless the lime silicate rock represents something more than a concentration of material in the limestone, a minimum decrease in volume of 60 to 80 per cent. must have taken place; that is the lime silicate rock occupies only 20 to 40 per cent. of the space occupied by the original limestone inclusion. As has been emphasized however, the garnetization took place after the solidification and fracturing of the granite-porphyry which completely surrounds the limestone blocks. If there had been important volume changes one or both of these rigid rocks should bear record of it. Sixty to eighty per cent. decrease in volume can not be accounted for by the small differences in porosity between the limestone and silicate rock (see accompanying table) nor by fractures because these are rare, nor by any supposition postulating open spaces large or small.

POROSITY OF IMPORTANT ROCK TYPES IN THE MACKAY DEPOSITS.

Determinations by George Steiger and W. C. Wheeler (Nos. 2–4).

Rock.	Locality.	Sp. gr. of Lumps.	Sp. gr. of Powder.	Pore Spaces, Per Cent.
1. Limestone	First bend, Alberta tunnel.	2.798	2.806	.4
2. Limestone	No. 3 crosscut, Alberta tunnel	2.728	2.729	—
3. Marble	No. 1 crosscut, Alberta tunnel	2.704	2.720	.5
4. Wollastonite rock	Cave tunnel, Champion group	2.786	2.805	.5
5. Garnet-calcite rock	Prospect 1,500 ft. NW., Copper Bullion tunnel	3.359	3.369	.4
6. Garnet rock	Alberta tunnel near mouth No. 5 crosscut	3.647	3.697	1.4
7. Fresh granite porphyry	Near end, Alberta tunnel	2.621	2.658	1.4

The joints in the granite porphyry along the periphery of the included blocks of limestone are accompanied by little or no gouge such as would be expected if they had been surfaces of sufficient readjustment to account for a shrinkage of 60 to 80 per cent. in the volume of the enclosed block. In cooling the magma probably closed in to some extent on the included limestone, but such an argument loses any weight which it might otherwise have because most of the garnetization is clearly subsequent to the solidification and fracturing of the igneous rock. Furthermore the lime silicate rock in places retains the bedding of the original limestone and elsewhere cuts as veins across bedded marble.

Source of Material.—As the physical relations of the granite-porphyry to the lime silicate rock inclosed within it preclude the possibility of important volume changes within the engulfed limestone blocks during their garnetization, it follows that the great excess of silica, alumina and iron in the lime silicate rock over that in the limestone was introduced and there seem but three possible sources: (1) meteoric waters leaching the material from the sedimentary rocks; (2) thermal waters of whatever source leaching the material from the solidified igneous rock, and (3) magmatic emanations from deeper and unconsolidated portions of the magma or from a source whence it also sprang.

If according to the first hypothesis the material is derived from the surrounding sedimentary rocks it appears impossible to account for the absence of metamorphism along the periphery of the intrusion. Adjacent to the ore bodies on the east border of the batholith the extensively jointed limestone dips toward the igneous contact, affording ideal conditions for meteoric waters to gather impurities from the stratified rocks during their descent and to deposit them during ascent along the less fractured granite-porphyry. Deposits in such situations, however, are notably absent. On the other hand, they occur as isolated bunches well within the batholith, where such meteoric circulation certainly would not attain its maximum development if indeed any water could enter the igneous rock while it was sufficiently hot to afford the heat requisite for metamorphism.

If under the second hypothesis the solidified and jointed granite-porphyry were the source of the foreign material, it would seem that the porphyry should show some evidence of material having been leached from it. The ferro-magnesian minerals which contain most of the iron, the element so abundantly added to the contact rock, should show some evidence of leaching, one of the changes to be expected being the transformation of biotite into muscovite. The quantity of diopsidized granite-porphyry is inconsequential in this connection. It is particularly noticeable, however, that the igneous rock, away from the immediate contact with secondary silicates and below the zone of surface weathering, is absolutely fresh. Even the products of hydrothermal metamorphism, so abundant in some contact metamorphic deposits, are almost entirely lacking here. Because of these features the second hypothesis which necessitates leaching of the adjacent porphyry does not appear worthy of further consideration.

The remaining hypothesis supposes that the silica, alumina and iron represent emanations from unconsolidated portions of the magma or from a source whence the granite-porphyry also sprang. This is a view that has received much support in recent years particularly in the writings of Lindgren, Kemp, Spurr,

Goldschmidt and others, but has been strongly opposed by Leith, Barrell, and recently by Uglow. In the Mackay deposits large blocks of limestone, completely surrounded by the igneous rock, were transformed into garnet rock after the solidification and extensive fracturing of the intrusion. There is abundant evidence of essentially constant volume during metamorphism, hence there must have been a vigorous transfer of material to account for the wide difference in composition between the original and the derived rocks. In order to derive one cubic meter of the garnet rock from an equal volume of the limestone, it is necessary to remove 259 kilograms of CaO, 1,100 of CO_2 and to introduce 314 kilograms of Al_2O_3, 511 of Fe_2O_3, and 1,269 of SiO_2. It is shown in preceding paragraphs that neither the limestone nor the granite-porphyry adjacent to the ore bodies can reasonably be assumed to have supplied the excess material of the silicate rock. This conclusion is based on direct observations and easily interpreted physical relations. In so far as it is absolute and in so far as the three possible sources of material are all inclusive, the further conclusion that deeper portions of the magma supplied the material is justified.

Until very recently reasoning of the above general nature, and the broad observation that in the numerous contact deposits which have been studied and of the diverse relations in individual deposits, the only common factor is the proximity of the igneous rock, have been the most reliable supports for the belief that watery magmatic emanations supply much of the material for contact deposits. Other direct observations, such as hydrous minerals and occluded carbon dioxide and water in igneous rocks, the gradation from igneous rocks to pegmatites and on into metal-bearing veins, and many others perhaps less convincing, have also supported the belief that most ore deposits are the products of solutions of magmatic origin. Recently this belief, firmly held by most investigators but doubted by some, has received strong support from the remarkably fruitful researches at the crater of Kilauea.[1] Gases collected directly from the molten lava

[1] Day, Arthur L., and Shepherd, E. S., "Water and the Magmatic Gases," *Jour. Wash. Acad. Sci.*, vol. 3, pp. 457–463, 1913.

contained 300 c.c. of water in a total estimated volume of 1,000 liters of gas. This direct observation that some magmas do contain large amounts of water makes far more rigorous the deductions based on well known field and laboratory evidence, for if one magma affords water the assumption that another has afforded water is abundantly warranted if supported by local field evidence. In the abstract then the student of ore deposits may consider two sources of solutions as equally credible and it remains for him to decide for each district which source is most probable in the light of local evidence. In the case of contact metamorphic deposits the alternative that the waters are meteoric implies, because of the transformations accomplished, that they were highly heated and, because of their relation to igneous contacts, that the intrusion supplied the heat. In the deposits at Mackay therefore it remains to assemble the evidence and see to which source of solutions it points.

Features to be Accounted For.—The features of these deposits which have a bearing upon this phase of the problem are: (1) The influence of joints and faults in the porphyry in directing the solutions; (2) the general fresh condition of the granite-porphyry; (3) the garnetization of the igneous rock; (4) the scarcity of lime silicates and the essential absence of ore even in the most favorable situations along the periphery of the batholith; (5) the relation of the garnet rock and the ore bodies to engulfed blocks of limestone; and (6) the vigorous transfer of material recorded in the transformation of comparatively pure limestone into massive garnet rock.

The bearing of each feature upon the source of the solutions will be considered separately.

1. The controlling influence of joints in directing the metamorphosing solutions is proved by the relations in many parts of the deposits, but it is believed that it would be the same whether the solutions were of meteoric or deep-seated magmatic origin. Both the igneous rock and the limestone were jointed and faulted before the metamorphism took place. It is obvious therefore that if the solutions emanated from the unsolidified magma they

did not come from that part immediately adjacent to the shoots of ore and garnet. The nearly vertical elongation and arborescent form of the shoots also indicates that the solutions did not come from the side, but rather that their movement was dominated by a vertical component.

2. The general fresh condition of the granite-porphyry away from the immediate vicinity of limestone inclusions appears equally explainable whether the solutions emanated from deeper portions of the batholith or were of the meteoric circulation. It may indicate either that they were confined to trunk channels and rock closely adjacent, or that they were incapable of attacking any of the constituents of the igneous rock until after coming in contact with limestone. The localization of the deposits with reference to included blocks of limestone and with reference to only certain of these, implies that both factors were of determinative importance.

3. The garnetization of the igneous rock implies solutions heavily charged with lime as well as alumina and iron, and it may appear at first thought that this preponderance of lime favors the hypothesis of solutions which entered through the surrounding limestone. On the other hand, every observed occurrence of garnet rock of porphyry derivation is closely associated with similar rock of limestone derivation. It is believed, therefore, that garnetization of the porphyry took place only where nearby limestone afforded the requisite lime. Meteoric solutions passing from without through the limestone into the solidified and jointed igneous rock would certainly have been charged with lime and thus the garnetization of the porphyry would not have been dependent upon *included* blocks of limestone. Furthermore if the waters came from without the batholith, and they were capable of garnetizing the porphyry, they would have done so along its periphery instead of only at considerable distances (locally 2,000 feet) within the igneous mass. It is believed therefore that the localized garnetization of the porphyry at once strongly supports the belief that the solutions were of magmatic origin, and refutes the alternative that they were of the meteoric circulation.

4. Similarly it seems impossible to account for the absence of ore and lime silicates of limestone derivation in structurally favorable situations along the periphery of the contact if we conceive the depositing solutions to have migrated toward the magma and there to have acquired heat and on ascent deposited material from solution. On this general supposition the solutions may have traveled upward along the contact or more likely upward and outward along courses determined by the combined effect of fracture zones and heated surfaces. Deposits of noteworthy importance thus situated, however, have not been found, and it seems entirely unreasonable to assume that external solutions should pass by the main contact and only become effective as metamorphosing agents when engulfed blocks of limestone are reached. Particularly is this so as the metamorphism took place after the solidification of the igneous rock, because after the magma became partly solidified the rocks along its periphery must have passed through all the degrees of falling temperature experienced by the included blocks. On the other hand, if the solutions emanated from the interior of the intrusion they would deposit at the point where they first came in contact with material with which they could react,—in this case with the inclosed blocks of limestone. It is believed therefore that the position of the ore bodies and lime silicate shoots of limestone derivation strongly favors emanations from the magma.

5. The relation of the lime silicate and ore shoots to limestone blocks and their absence well removed from such blocks seems to indicate further that the presence of limestone was an essential factor in the metamorphism. If it was thus necessary to derive vast amounts of lime from limestone it is obvious that the metamorphosing solutions were not saturated with respect to calcium compounds nor did they contain sufficient to become saturated except at places where limestone was available and the lime utilized. This dearth of lime is readily accounted for if the solutions emanated from the magma, for calcium compounds are exceedingly rare in volcanic sublimates and their presence in magmatic waters is doubtful. If on the other hand meteoric waters

descended along structure planes to the hot igneous contact they should have become saturated with lime during descent and have been available for garnetization in the absence of engulfed blocks of limestone. In the abstract, however, the possibility remains that meteoric waters may have been delivered to the lower part of the contact and not to the upper and that there garnetization did take place. This possibility was entertained in the field, but finds no support in the structural relations of the surrounding limestone to the batholith nor in the character of the beds which underlie the limestone series. The extent of erosion since intrusion is not known, but the granite now outcrops through a vertical range of nearly 2,500 feet and it is probably reasonable to assume a cover of not less than 1,000 feet. In the absence of faults to cut off the flow through beds that dip toward the contact, it must be concluded that fully as much water would have been delivered to that part of the contact now exposed as to any deeper part. Indeed the many observations in deep mines indicate that much more meteoric water would be delivered at levels above 3,500 feet than at levels below that depth. This does not mean necessarily that meteoric waters would not reach to lower depths but that their circulation would be more active at higher levels. It is considered unreasonable, therefore, to assume that more solutions of meteoric origin could have been delivered to the magma at greater depth than within the 2,500-foot zone now exposed. Of the two possibilities, therefore, (*a*) that the solutions emanated from the magma, and (*b*) that they descended along structural planes and invaded the hot igneous rock from the surrounding limestone, the dependence of the solutions upon the included limestone blocks for lime strongly favors the alternative that they emanated from the batholith.

6. The vigorous transfer of material involved in the transformation of comparatively pure limestone into massive garnet rock emphasizes still further the anomalous absence of lime-silicates along the periphery of the batholith if it be assumed that the solutions invaded the magma from without. If on the other hand they emanated from deeper portions of the

intrusion there is no reason to believe that they escaped laterally, for the form of the ore shoots indicates that their paths approached closely to the vertical. At the point of issue from the igneous mass into the overlying limestone garnet probably formed, but has been removed by erosion. Also at the intersection of the Alberta fault with the limestone, garnet would be expected and indeed does occur, but only locally (Fig. 82). The garnet vein on White Knob extends vertically across overlying beds of marble. The absence of even a discontinuous peripheral zone of lime silicates, therefore, indicates that solutions capable of such intense metasomatism did not transgress the igneous rock from the surrounding limestone. This indication is vastly strengthened because there is absolutely no reason, structural or otherwise, for believing that meteoric solutions did not tend just as strongly, if not more so, to approach the igneous rock at the levels of the present accidental surface as at greater depths.

Summary.—In preceding paragraphs the bearing of the six prominent features of the Mackay deposits upon the source of the metamorphosing solutions have been considered. In this consideration very little of theory has been introduced. An effort has been made in each case to utilize broad physical relations involving only a short step between observation and interpretation. Four of the six major features of the deposits which must be accounted for (Nos. 3, 4, 5 and 6, p. 350–352) may be readily explained on the assumption that the solutions came from deeper portions of the magma, and refute the alternative view that they entered the igneous rock from the surrounding limestone. The two other prominent features (Nos. 1 and 2) may be interpreted perhaps equally well on either assumption: certainly neither favors the meteoric circulation over magmatic emanations.

It is believed, therefore, that the evidence of the Mackay deposits is overwhelmingly in favor of emanations from deeper portions of the batholith. The alternative that the metamorphism was caused by a meteoric circulation stimulated by the intrusion is not only improbable but seems altogether untenable in view of the several features that must be accounted for.

THE SOLUTIONS, A DIFFERENTIATE FROM THE GRANITE-PORPHYRY MAGMA.

From the discussion in previous sections it is concluded: (1) That the garnetization at Mackay took place after the solidification and jointing of *at least* the outer few hundred feet of the batholith; (2) that the marmorization probably occurred in large part at the time of intrusion; (3) that the metamorphism was not effected by a succession of distinctly different solutions, but rather by a single solution that underwent gradual change as the process proceeded so that in general the metallic minerals formed later than the silicate minerals; (4) that the great amount of iron, silica and alumina represent additions from the magma and can not be accounted for by assuming either a concentration of impurities in the original limestone inclusions, or by leaching from the external limestone.

The writer's conception of the succession of events which brought about the observed relations is as follows: As the intrusion came to rest in the limestone, emanations consisting largely of water gas escaped into the overlying beds, causing extensive marmorization, as on White Knob. This effect was essentially a rearrangement of material already present in the limestone and certainly did not afford important contributions. This period may have been of short duration compared with the active one which began later. A period of essential quiescence during which marginal solidification of the magma was accomplished seems to have followed. This solidified zone was fractured. Then solutions capable of energetic metasomatic replacement escaped through the fractures.

The physical relations of the deposits lend strong support to the conception as outlined thus far. Further, we may conceive, (1) a parent magma reservoir whence sprang at different times both the granite-porphyry magma and the metamorphosing solutions, or (2) that the solutions escaping during metamorphism were distributed rather uniformly through the granite-porphyry magma at the time it came to rest and that their expulsion accompanied its crystallization. Of these alternatives the second

is favored by local evidence. If the differentiation had taken place in a magma reservoir remote from the place now occupied by the granite-porphyry it seems strange that material of the second advance should follow paths wholly within the material first injected. It seems rather that solutions advancing subsequent to this injection would have followed the joints of the limestone adjacent to the granite-porphyry. Furthermore, if the metamorphism is not closely dependent upon the local igneous mass it is difficult to account for the unaltered aplite dikes which traverse garnet areas. The metamorphism certainly antedates the aplites or accompanied their injection for in no place are they metamorphosed as is other igneous rock similarly situated. Indeed they are believed to be younger than the metamorphism for if they represent channels along which traveled the iron-laden solutions which supplied material for the garnet rock it would seem that they should contain iron compounds, in addition to feldspar and quartz, at places where they traverse garnet-magnetite rock. As aplites are quite generally considered to be differentiates from lower parts of the igneous mass enclosing them, it is necessary to believe that the ore solutions were operative before the complete crystallization of the local mass of granite-porphyry. If the ore solutions came from a deep-seated parent magma, it follows that they advanced into the granite-porphyry through a part of it which was still in a molten condition and the problem of their further expulsion from the molten interior into the fractured shell would be the same as if they had always been a part of the magma. It is concluded, therefore, that the second hypothesis alone need be considered, and it remains to form some conception as to how the elements of the metamorphosing solutions may have been concentrated and expelled after the crystallization and fracturing of an outer shell.

In elaboration of this conception the chilling of the peripheral zone of the magma may be conceived as effecting a barrier to the escape of solutions. As the cooling progressed inward these may well have been concentrated inward and downward by fractional crystallization. It is probable that such concentration could

not continue indefinitely but there seems no reason why it should not persist during the formation of a shell several hundred feet thick. Fractures traversing this shell would afford avenues of escape for the solutions which, because of long continued concentration, may well be considered capable of the vigorous transfer of material recorded by the lime silicate rock.

This general conception fits the conditions at Mackay better than any other which has been considered, as it is thus possible to account for a lapse of time between a period of marmorization at the time of intrusion and one of garnetization at a subsequent time. The chief difficulty is to conceive a workable mechanism for the concentration toward the center of the magma of volatile constituents which normally would tend to escape outward. It is probably safe to assume that crystallization of the magma began at the periphery and progressed inward, a transition zone of partly crystallized material always separating the solid shell from the liquid core. How wide this transition zone was is entirely speculative. If there is a backward concentration of such material as is not incorporated in the final rock, however, its elimination must take place from this zone of active crystallization. Here the concentration of such excess material as water vapor would be greatly raised because of the decrease in the total volume of liquid components incident to the growth of crystals. Diffusion from this zone of higher concentration would tend to establish equilibrium throughout the entire mass, thereby raising in it the concentration of materials comprising the residual fluid magma, unless fractures or porosity in the solidified shell allowed them to escape outward. It is a matter of observation, however, that the outward escape was along fractures; in the Alberta workings along a considerable fault, implying a shell at least a few hundred feet thick. Further, the solutions causing garnetization were more highly concentrated with respect to iron, silica, and alumina than those expelled at the time of intrusion, which only caused marmorization. It is suggested therefore that the residual material found a way into unsolidified portions of the magma. Its transfer may have been by diffusion although this seems to

involve serious difficulties due to the extreme slowness of the movement as pointed out by Becker.[1] Harker, on the other hand, believes that "diffusion proceeds freely in a cooling rock magma long after the increasing viscosity has rendered bodily movement impossible."[2] It may be that a combination of this idea and a conception of differentiation favored by Pirsson[3] in his discussion of the Highwood laccoliths meets the requirements of the problem. Pirsson's explanation of differentiation within a laccolith postulates "a combination of convection currents and the tendency to crystallize first at the outer walls." He believes that the heat set free by crystallization and "the resulting concentration of the chemically combined water vapor in the magma . . . would tend to counteract the increasing viscosity due to cooling." The convection currents would be upward in the center and downward along the sides. Thus crystallization would proceed most rapidly well down on the sides of the magma, and as it proceeded "the edges of the outer crust would rise more and more toward the top, finally spreading over it, and as a result the crust should be thinner on the top than elsewhere." It seems to the writer, however, that diffusion, even though a slow process and one perhaps not effective through considerable distances, must be called upon to deliver the material to the convection currents. Viscosity in the outer part of the transition zone between material wholly solid and that wholly liquid certainly would be so great that the material close to the solid mass would not be involved in a convection movement. The conception that the crust was thinner on top is favored by the greater observed metamorphism on top of the Mackay intrusion than along its sides.

If through some such conception as outlined above it is possible to account for a backward concentration into the magma it is easy to picture the expulsion of the residual fluid material through fractures developed in the outer shell, and thus to account for a

[1] Becker, G. F., "Computing Diffusion," *Am. Jour. Sci.*, 4th ser., vol. 3, pp. 280–286. 1897.

[2] Harker, Alfred, "The Natural History of Igneous Rocks," p. 319, 1909.

[3] Pirsson, L. V., "Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana," Bull. U. S. Geol. Survey No. 237, pp. 187–190, 1905.

lapse of time between marmorization at the time of intrusion and metasomatism subsequently. When in the central portion of the magma crystals have become so numerous that they may be likened to a mass of gravel saturated with steam under great pressure, fractures in the inclosing crust would relieve the pressure and readily allow the escape of the concentrated residual material. The volatile residuum thus escaping by expansion would be augmented by fluid material squeezed out by a crowding together of the crystals because of reduced resistance to external pressure.[1] The aplite dikes may be an end product of this later process.

This general conception may be of somewhat general application for its key-note is the concentration of the metamorphosing constituents in the magma. If this concentration is very high, garnetization will accompany the rise of the magma into regions of less pressure, or may even progress well in advance of the intrusion; if it is low, backward concentration will be necessary before garnetization can take place. Several so-called periods or waves of metamorphism may merely mean fracturing, sealing of the fractures and refracturing. The fractures may be sealed by pegmatitic or aplitic material or progressive thickening of the shell may form a barrier across their inner ends.[2]

[1] Harker, Alfred, "The Natural History of Igneous Rocks," p. 323, 1909.

[2] The above conception, except perhaps the bearing of concentration as suggested in the last paragraph, is merely an adaptation to the occurrence at Mackay, of different conceptions already expressed in the literature. The following references will suffice to illustrate; Vogt, J. H. L., "Problems in the Geology of Ore Deposits, Genesis of Ore Deposits," 1901, pp. 641–658. Lindgren, W., "The Genesis of the Copper Deposits of Clifton-Morenci," Prof. Paper U. S. Geol. Survey No. 43, 1905, pp. 218–223. Spencer, A. C., "The Magmatic Origin of Vein-forming Waters in Southeastern Alaska," Amer. Inst. Min. Engrs., Bi-Monthly Bull., 1905, pp. 973–974. Spurr, J. E., "A Theory of Ore Deposition," Economic Geology, vol. 2, 1907, pp. 781–795. Iddings, J. P., "Igneous Rocks," vol. 1, 1909, pp. 260–276. Knopf, Adolph, "Some Features of the Alaska Tin Deposits," Economic Geology, vol. 4, 1909, pp. 221–223. Emmons, S. F., "Cananea Mining District of Sonora, Mexico," Economic Geology, vol. 4, 1910, pp. 334–335. Goldschmidt, V. M., "Die Kontacktmetamorphose in Kristianiagebiet," 1911, p. 108. Spurr, J. E., "A Theory of Ore Deposition," Economic Geology, vol. 7, 1912, pp. 485–486.

A GEOLOGIC AND MICROSCOPIC STUDY OF A MAGMATIC COPPER SULPHIDE DEPOSIT IN PLUMAS COUNTY, CALIFORNIA, AND ITS MODIFICATION BY ASCENDING SECONDARY ENRICHMENT.[1]

H. W. TURNER AND A. F. ROGERS.

I. GEOLOGY.

H. W. TURNER.

The copper deposits described in this paper are situated in Plumas County, California, on the west slope of the east range of the Sierra Nevada to the northeast of Indian Valley and are embraced in the claims of the Engels Copper Mining Company. The nearest railroad point is Keddie on the Western Pacific R. R., about thirty miles distant by wagon road. The location is shown on the accompanying sketch map (Fig. 90).

The general geology of the region is described in Bulletin 353 of the U. S. Geological Survey by J. S. Diller, which, contains two geological maps.

In that portion of the district northeast of Indian Valley, with which we have to do, the prevailing rock is granitic in character and is designated granodiorite by Diller, for mapping purposes, although in the neighborhood of the mines all the dioritic rocks are basic and contain but little free quartz, as will appear in the detailed descriptions of Professor Rogers. This dioritic rock is intrusive in Jura-Trias and Carboniferous sediments and associated meta-andesites and meta-rhyolites, but all the ore bodies referred to in this paper are in the dioritic series.

The copper deposits of the main Engels mine occur in a fresh massive dioritic rock in which most of the fractures, except those referred to under pegmatites, are distinctly post-mineral. The most abundant metallic minerals are magnetite, bornite and chalcopyrite. Pyrite is conspicuously absent. These metallic

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lapse of time between marmorization at the time of intrusion and metasomatism subsequently. When in the central portion of the magma crystals have become so numerous that they may be likened to a mass of gravel saturated with steam under great pressure, fractures in the inclosing crust would relieve the pressure and readily allow the escape of the concentrated residual material. The volatile residuum thus escaping by expansion would be augmented by fluid material squeezed out by a crowding together of the crystals because of reduced resistance to external pressure.[1] The aplite dikes may be an end product of this later process.

This general conception may be of somewhat general application for its key-note is the concentration of the metamorphosing constituents in the magma. If this concentration is very high, garnetization will accompany the rise of the magma into regions of less pressure, or may even progress well in advance of the intrusion; if it is low, backward concentration will be necessary before garnetization can take place. Several so-called periods or waves of metamorphism may merely mean fracturing, sealing of the fractures and refracturing. The fractures may be sealed by pegmatitic or aplitic material or progressive thickening of the shell may form a barrier across their inner ends.[2]

[1] Harker, Alfred, "The Natural History of Igneous Rocks," p. 323, 1909.

[2] The above conception, except perhaps the bearing of concentration as suggested in the last paragraph, is merely an adaptation to the occurrence at Mackay, of different conceptions already expressed in the literature. The following references will suffice to illustrate; Vogt, J. H. L., "Problems in the Geology of Ore Deposits, Genesis of Ore Deposits," 1901, pp. 641–658. Lindgren, W., "The Genesis of the Copper Deposits of Clifton-Morenci," Prof. Paper U. S. Geol. Survey No. 43, 1905, pp. 218–223. Spencer, A. C., "The Magmatic Origin of Vein-forming Waters in Southeastern Alaska," Amer. Inst. Min. Engrs., Bi-Monthly Bull., 1905, pp. 973–974. Spurr, J. E., "A Theory of Ore Deposition," ECONOMIC GEOLOGY, vol. 2, 1907, pp. 781–795. Iddings, J. P., "Igneous Rocks," vol. 1, 1909, pp. 260–276. Knopf, Adolph, "Some Features of the Alaska Tin Deposits," ECONOMIC GEOLOGY, vol. 4, 1909, pp. 221–223. Emmons, S. F., "Cananea Mining District of Sonora, Mexico," ECONOMIC GEOLOGY, vol. 4, 1910, pp. 334–335. Goldschmidt, V. M., "Die Kontacktmetamorphose in Kristianiagebiet," 1911, p. 108. Spurr, J. E., "A Theory of Ore Deposition," ECONOMIC GEOLOGY, vol. 7, 1912, pp. 485–486.

A GEOLOGIC AND MICROSCOPIC STUDY OF A MAGMATIC COPPER SULPHIDE DEPOSIT IN PLUMAS COUNTY, CALIFORNIA, AND ITS MODIFICATION BY ASCENDING SECONDARY ENRICHMENT.[1]

H. W. Turner and A. F. Rogers.

I. Geology.

H. W. Turner.

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oxides and sulphides appear to me to have crystallized out from the original magma in the same way as the feldspar, hornblende, pyroxene and biotite. All appear to be of the same general period of formation although the metallic oxides and sulphides are largely interstitial between the silicate minerals and thus later in crystallizing out. In some sections, however, there are distinct inclusions of magnetite and copper sulphides in the silicate minerals, suggesting that these metallic grains formed before the enclosing silicate minerals. The evidence presented by Professor Rogers that the sulphide solutions have corroded and replaced the silicate minerals, while showing the sulphides to be later, does not appear to me to necessitate a time interval of any mangitude, for as soon as a phenocryst is formed in a given magma, it is at once exposed to corrosion and replacement by the magma itself, and the fact that most of the metallic minerals are interstitial between the grains of the silicate minerals is in itself no more evidence of the introduction of the metallic minerals at a *much* later period than is the case with interstitial quartz in quartz-diorites and granodiorites. In these granular rocks the quartz often fills the spaces between the more or less idiomorphic feldspar and hornblende, and is plainly later and yet the quartz is regarded as a constituent of the original magma and in that sense an original mineral.

In the case of the Engels deposits, there has been no dynamo-metamorphism and no hydro-thermal metamorphism. The constituents of the fresh diorite show no evidence of crushing and recrystallization but the larger part of the metallic constituents are later than the silicates and must have been a part of the original magma, or else introduced in solutions which only corroded the original silicates and did not produce sericitization, carbonatization, silicification, etc., of the diorite, as would be the case if formed by ordinary hydro-thermal aqueous solutions.

The massive diorite which forms the gangue of the copper ore is best seen in tunnel No. 5, a plan of which is here presented on which those portions of the diorite containing 2 per cent. or more of copper are represented as ore (Fig. 91). Nearly all the rock

of the workings in this level was sampled and only two samples showed no copper. The ore of commercial value contains about 75 cents per ton in gold and silver.

The portions of the mass that are represented as ore form more or less irregular areas which nevertheless seem generally to have

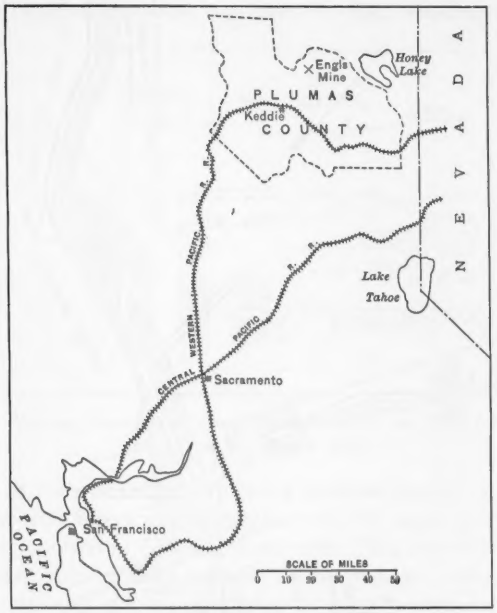

FIG. 90. Sketch Map of North Central California, showing the Location of the Engels Mine.

a northeasterly trend and to extend down vertically. This is very noticeable with the main ore body of No. 5 tunnel which is about 550 feet long, 25 feet wide (Fig. 91) and stands in a nearly vertical position as will be seen in the cross section of the mine (Fig. 92).

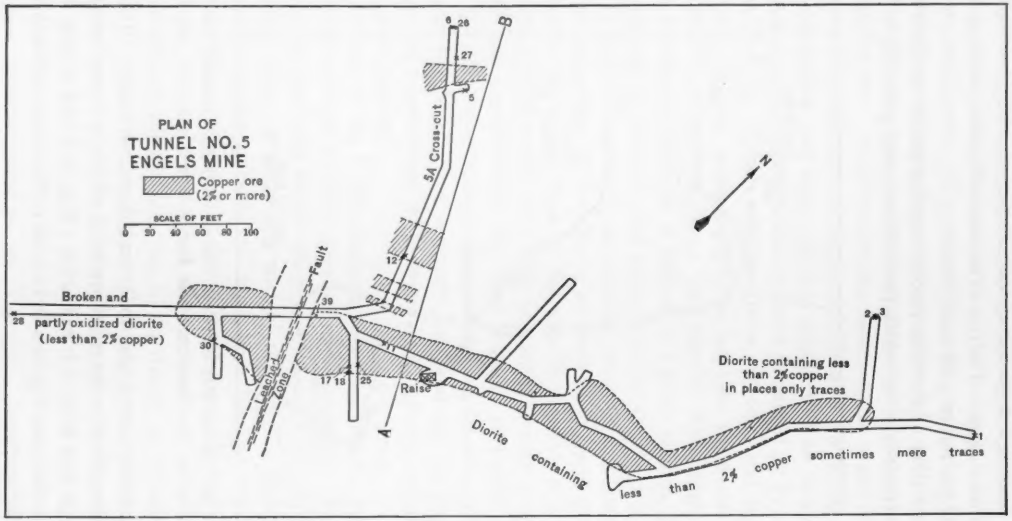

FIG. 91. Plan of Tunnel No. 5, Engels Mine.

On the map there is noted a strong fault. This stands nearly vertical, and the rocks to the southwest of this fault are more or less fissured and broken and altered by downward percolating surface waters, while the rocks and ores of the area to the northeast are essentially fresh and unoxidized. There is no megascopic evidence of the deposition of secondary sulphide ores along this fault or any other similar fractures in other workings. The

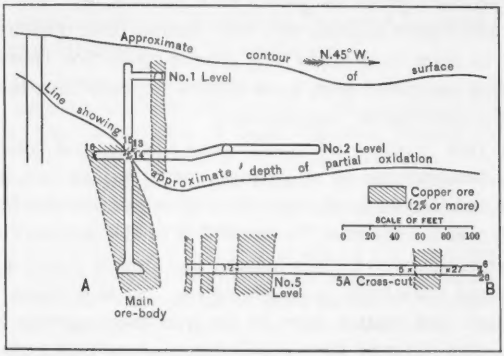

FIG. 92. Vertical Cross-section through Ore-Bodies at the Raise (along line *AB* of Fig. 91), Engels Mine.

diorite of the area to the northeast is hard and dense. It varies in grain from medium to fine grained and the larger part of the commercial ore is in the fine grained rock. At a few points there is a fairly sharp contact between the medium and fine grained diorite; at other points a gradation between the two, but at no point was there a dike of one variety in the other and the conclusion was drawn that they are both of the same age of consolidation and from the same magma. The only distinctly later rock or ore is the pegmatitic material hereafter noted, except the products of surface oxidation. The rocks and ores which were submitted to Professor Rogers for a detailed study came mostly from the unoxidized area in No. 2 and No. 5 tunnels and the numbers shown on the map correspond to the numbers given in his paper.

All petrographers recognize that metallic oxides and sulphides do occur as original constituents of igneous rocks, but when these metallic constituents appear in abnormal amount, and especially when there is evidence of the dynamo-metamorphism of the associated igneous rocks, some geologists hold that the ores were introduced later and by aqueous solutions. Nevertheless, the constant association of chrome iron ore and platinum with olivine rocks, of titaniferous magnetite with gabbros, etc., and certain nickel and copper sulphide ores with various basic igneous rocks, appear to point indubitably to a genetic connection between the rocks and associated ores, even if these deposits have been subsequently modified or recrystallized.

That rock magmas differentiate into siliceous and basic facies is considered proven by all petrographers, and, in fact where a deep seated magma is subsequently well exposed so that it can be studied over a wide zone, the variability of the samples collected at different points as to their mineral constituents is now a matter of common knowledge to all geologists. Some portions will be more basic and contain more of the iron and magnesia-bearing silicates and more of the metallic components, both oxides and sulphides, than others. We find a gabbro passing by loss of feldspar into a rock composed wholly of pyroxene or hornblende and accessory minerals and no one questions differentiations of this sort, but if the metallic constituents should separate and form ore masses, especially if these be sulphides, we become, so it seems to me, unduly skeptical. There seems to be a tendency to become alarmed at the conception of a sulphide solution forming part of a magma, since most sulphides are undoubtedly formed from aqueous solutions. An interesting example (but doubtfully bearing on this question) of the formation of a deposit of a sulphide of copper from an igneous solution or matte was noted at the blast furnace of the Kyshtim copper mines in Russia in 1911. The bricks forming a part of the settler of one of the furnaces were taken out and found to be heavily impregnated with newly formed yellow sulphide, apparently chalcopyrite,

which had separated out from the matte.[1] It is a matter of regret that the exact conditions under which this new ore deposit took place were not noted. Specimens of these bricks are in the Kyshtim geological collection.

To what extent the phenomena of the artificial molten magmas of smelters apply to molten magmas of the earth's interior is, to be sure, as yet an open question. Nevertheless, the following explanation of the method of formation of the Sudbury pyrrhotite copper-nickel ore deposits by Professor Reginald E. Hore[2] deserves consideration in this connection.

"So far as known molten silicates are miscible in all proportions. Molten sulphides, however, will not mix in all proportions with molten silicates. One cannot state off hand, therefore, whether the cooling magma would behave as one or two or more solutions. From a consideration of the end products—the norite and ore bodies—it seems to the writer that before solidification took place, the magma, with decrease in temperature, had separated very imperfectly into two solutions. One of these was composed chiefly of the constituents of the silicates and the other chiefly of the constituents of the sulphides. Each solution contained a comparatively small portion of the constituents of the other. The sulphide being heavier sank to the bottom. The process would be much like the separation of matte from slag with the very essential difference that none of the furnace man's precautions to effect a clean separation were taken. . . . Thus the silicate solution was saturated with sulphides and on cooling below the temperature beginning the freezing interval, it is probable that the sulphides would be among the first formed minerals. If in the silicate solution there were any bodies of the sulphide solution there would doubtless be a change in the composition of the solutions in contact. After the main mass of the silicate solution became solid, there would on further cooling be a second deposition of sulphide from the included solutions. We would expect as a result of such processes to find, and we do find, large masses of norite specked with grains of early formed sulphides and with occasional patches of later formed sulphides, and from the sulphide solution massive ore with early formed silicates in it."

Professor Hore, however, regards some of the Sudbury deposits as secondary, having formed from the original primary deposits, especially where crushing and faulting has occurred.

[1] The sulphides in a copper matte are usually supposed to be Cu_2S and FeS.
[2] Quarterly Bull., Canadian Mining Institute, No. 21, pp. 86–88, 1913.

Professor Beck's latest expression in regard to magmatic sulphide ores is as follows:[1]

"The problem of the sulphides in the gabbros, norites and diabases was more difficult. He who is familiar with the literature on the important deposit of Sudbury as well as that on the small occurrences at Sohland, on the Spree and Schluckenau, knows how difficult it was for geology to arrive at a generally accepted genetic conception of these ores. The microscope has shown that the old view of the magmatic nature of these ores applies to the extent that a part of the existing nickeliferous pyrrhotite and chalcopyrite actually must have segregated direct from the molten magma; and in case of the great Canadian deposits this was by far the greater part. On the other hand, thin sections show that probably a thermal solution and redeposition of finely divided ore particles took place, giving rise to the formation of compact secondary masses of ore. A metamorphism of the rock preceded this redeposition, so that the secondary green hornblende, which is attached to the pyroxenes in delicate fringes, is in turn surrounded by pyrrhotite. The nickel content of the pyrrhotite is now also explained."

Pegmatite.—Returning now to the Engels deposit, after the solidifying of the diorite magma, numerous, nearly straight, but non-persistent, cracks or fissures formed and the residual solutions of the magma filled the fissures with feldspar, quartz, chlorite, epidote, calcite and chalcopyrite, all apparently original, forming narrow veins from one to eight inches in width. These little veins are therefore distinctly later than the main deposit and may be regarded as belonging to the pneumatolytic period, in the same sense as do the granitic pegmatites.

Post-Mineral Fractures.—Almost everywhere the diorite mass contains numerous joint planes of which a nearly horizontal and a nearly vertical set are most prominent. These have been taken advantage of in driving, so that a horizontal joint often forms the roof of a portion of a drift and vertical joint planes, the walls. There are also inclined partings or joints. *So far as examined, the joint seams do not contain sulphides* and if this is substantiated, it is evident they were formed *after the period of mineralization,* which would be evidence of the magmatic origin of

[1] Address before the Royal School of Mines, Freiburg, October 3, 1911. Translation from *E. and M. Journal,* May 31, 1913.

the deposit, as they were certainly formed after the consolidation of the magma, and presumably formed after the pegmatite. Other post-mineral stresses are apparently of comparatively recent date resulting in the formation of faults and a broken zone in a portion of the mine.

Outside of the plainly post-mineral faulted zone there are no strong, persistent fissures or crushed zones with accompanying gouge streaks and striations such as are essential in deposits formed by ordinary hydrothermal waters for the waters must have avenues through which to circulate. The strongest fissure in the mine, outside of the post-mineral faulted zone previously referred to, extends along the south side of the main ore body from station 13 to the face a distance of about 240 feet. There is water dripping from this fissure which shows only traces of gouge and is a rough fissure along which but little movement has taken place. There are also some less persistent fissures at other points, in one or two cases with good ore along them, but mostly cutting obliquely across the general strike of the ore zones, suggesting their later origin.

In the decomposed diorite of No. 2 and No. 3 tunnels there are however clay seams showing evidence of movement in distinct slickensides. These movements were presumably in part due to the swelling of the rocks from absorption of water in the same way that similar movements take place in clay and serpentine, although in the upper tunnels the striated clay fissures probably followed cracks of earlier origin.

The only fissures in the diorite that are certainly connected with mineralization are those filled with pegmatitic material. These usually persist so far as can be told in the underground workings for a short distance only—less than 50 feet.

Oxidation and Secondary Ores.—There is shown on the cross section of the mine (Fig. 92) a zone of oxidation. In reality the oxidation is very irregular, and many of the compact pieces of diorite in this zone will if broken show fresh original sulphides in their inner portions. At and near the surface, and at the fractured zones near the faults above described, many of the frac-

tures and joint planes in the diorite contain seams of green copper silicate (chrysocolla) plainly of secondary origin and the rotten diorite itself is more or less impregnated with green secondary copper ore. Moreover in No. 3 tunnel, there is a large amount of rotten diorite showing no visible copper minerals, but which on assay often is proved to contain over 1 per cent. of copper. It seems likely that the copper occurs in such rotten diorite as sooty glance or covellite, which in small amount cannot be determined except chemically and this has not been done. There is, however, no definite secondary sulphide zone of enrichment, unless the 1 per cent. ore just noted is regarded as a zone of enrichment. The unoxidized ore is compact, and not having been fractured or crushed except locally, the surface waters have not to any extent percolated downward except along occasional fractures and the seeping downward of surface waters is an essential feature in secondary enrichment. Moreover the absence of pyrite is another factor in the preservation of sulphide ore in its original condition, for chalcopyrite and bornite decompose and form soluble sulphates much less readily than pyrite, and the percolating surface waters that bring about secondary enrichment get their solvent power largely from the sulphuric acid derived from sulphates.

Conclusions.—In nearly all mines of the ordinary vein character, when the country rock is massive granite or diorite, the following succession may be assumed:

1. Consolidation of the magma, usually succeeded by tension cracks often filled by the residual magma forming pegmatite dikes or veins.

2. Jointing of rocks.

3. Fracturing and fissuring, the general course of the fissures often being guided by the pre-existing joints.

4. Introduction of the epigenetic vein deposits through mineral bearing solutions, with accompanying hydrothermal alteration of the wall rocks, producing silicification, sericitization, carbonatization, etc. These solutions fill the fissures with gangue minerals and ores and to some extent the joint planes and im-

pregnate the walls of the fissures to a greater or less extent, in most cases depositing pyrite.

This program does not appear to have been effective in the geological history of this deposit. In the Engels deposit we appear to have the following:

1. Consolidation of the diorite, accompanied by the deposition of copper minerals. This is the magmatic period.
2. Filling of tension cracks or fissures in the diorite by pneumatolytic solutions forming pegmatite.
3. Jointing of the rocks.
4. Extensive faulting and fracturing in one zone.
5. Surface oxidation resulting in the deposition of chrysocolla, and *possibly* earthy glance or covellite.

There may be further noted in the fresh ore:

1. No hydrothermal metamorphism.
2. No dynamo-metamorphism.
3. No contact-metamorphism, as the older rocks in which the diorite is intrusive, are nearly five miles away at the nearest point.

Superior Mine.—The Superior Mine, belonging to the Engels Copper Mining Company, is situated about three miles southwest of the main Engels mine. It is likewise in a granitic rock, but here the copper minerals, instead of being diffused through the rock irregularly, are chiefly deposited along joint planes, and appear more like veins. The ore is bornite and chalcopyrite in a gangue of a green fibrous hornblende resembling actinolite, and the copper sulphides and the hornblende appear to have deposited together in the joint seams of the granitic rock. The ores are, therefore, distinctly later than the country rock, but it is possible that they belong to the same period as the pegmatite (pneumatolytic) ore bearing veinlets of the Upper Engels mine. In the tunnel by Lights Creek in Superior No. 1 claim, the joint seams are coated with pyrite, and this is the only place on the property where pyrite was observed. This pyrite is plainly due to aqueous solutions.

Extent in Depth.—Assuming the magmatic origin of the Engels ore, the interesting question comes up as to its probable

extent in depth. There appears to be no geological reason why ore bodies of this nature should not extend to a considerable depth, not necessarily as a single ore body, but possibly as isolated bunches or lenses.

Little Namaqualand.—In Cape Colony, in Little Namaqualand, there are a number of mines working on ores similar to those of the Upper Engels mine and some comparison may therefore be made. In general the Namaqualand formation is gneiss, penetrated by a series of basic dikes which contain bornite and chalcopyrite, as well as some pyrrhotite and molybdenite and a little chalcocite. These deposits have been examined by English and German geologists, who state the copper minerals are primary and of magmatic origin. The commercial ore bodies are in general irregular, and give out in all directions, although being of the nature of dykes they have taken together a more or less definite trend or "run."

Kuntz represents the Tweefontein Mine as showing in vertical section three ore bodies, the deepest reaching to about 860 feet from the surface. Not having the usual fissures of ordinary veins for a guide, in some of the mines exploitation work has been very irregular and considerable work has been done that revealed no deposits of value.

Only partial statistics of the production of Namaqualand have been obtained. In the years 1852–1862, 1883–1904 and the year 1907–8 of O'okiep Mine, the total production amounted to 1,069,704 long tons of dressed ore averaging 20.3 per cent. copper and thus containing gross 216,950 long tons of metallic copper.

In addition the Namaqua Copper Company for the year 1912 reports a production of 42,841 tons of ore raised at the Tweefontein and an ore reserve of 99,598 tons.

Professor A. W. Rogers, Director of the Geological Survey of the Union of South Africa, has in press a report on the Namaqualand copper ores.

After this description was written, there appeared in Economic Geology, June, 1913, two papers on magmatic sulphide

ores; one by Knopf on a pyrrhotite deposit at Elkhorn, Montana, and one by Bagg on a pyrrhotite ore body in Wisconsin. In both cases the authors regard the ores as due to direct segregation from the magmas and not to introduced solutions.

II. Mineralogy and Petrography.

Austin F. Rogers.

A suite of about thirty copper ores and associated rocks collected by Mr. H. W. Turner at the Engels mine in Plumas County, California, was submitted to the writer for detailed study.[1] As this proved to be a magmatic sulphide deposit with evidence of later sulphide enrichment by ascending alkaline solutions, the results of the examination are described in some detail.

The writer desires to express his thanks to Mr. H. W. Turner for an opportunity to study the specimens from the Engels Mine, to Mr. G. W. Jordan for the chemical analyses, and to Prof. C. F. Tolman, Jr., for valuable suggestions.

THE ROCK TYPES.

Norite-diorite.—The copper minerals occur for the most part in minute specks in a rather basic igneous rock which may be designated norite-diorite as both hypersthene and hornblende are usually present and as the plagioclase is Ab_1An_1. The silica percentage of about 46 per cent. (No. 2, $SiO_2 = 45.5$ per cent.; No. 16, $SiO_2 = 45.9$ per cent.) proves it to be rather basic.

The rock specimens show considerable variation in mineral constituents and in coarseness of grain. With a few exceptional types to be described later the rocks vary from a rather fine-grained (.5 mm.) plagioclase-hypersthene rock (Fig. 93) to a coarse-grained (2 mm.) plagioclase-hornblende rock (Fig. 94). The dominant mineral in most of the rocks is a plagioclase with albite twinning. The maximum extinction angle of 28° in sections cut normal to the albite twin-lamellæ indicates andesine-

[1] Through the kindness of Mr. Turner these specimens are deposited in the geological collections of Stanford University.

labradorite, Ab_1An_1. The plagioclase shows no zonal structure, but one slide (no. 15, Fig. 95) shows secondary enlargement of narrow rims which extinguish parallel to the set of narrow twin-lamellæ.

FIG. 93. Hypersthene-plagioclase rock (No. 16), × 50. *f* = plagioclase, *hy* = hypersthene, *b* = biotite.

The hypersthene occurs in anhedra with faint pleochroism from pale-greenish to pale reddish-brown. The hornblende is a pale green variety with maximum extinction angle of 20°

and occurs in large irregular anhedra. Some of the slides show a colorless monoclinic pyroxene, probably diopside, with a maximum extinction angle of about 45°. The diopside usually occurs

FIG. 94. Hornblende-plagioclase rock (No. 2), × 50. *f* = plagioclase, *ho* = hornblende.

as cores within the hornblende. Biotite is prominent in some of the rocks, while in others its place is apparently taken by chlorite.

The accessory minerals include apatite, epidote, titanite, calcite, analcite, and interstitial quartz. The calcite and analcite both

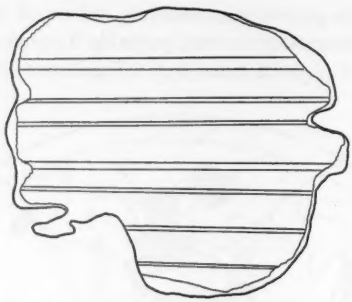

FIG. 95. Plagioclase, showing secondary enlargement (No. 15).

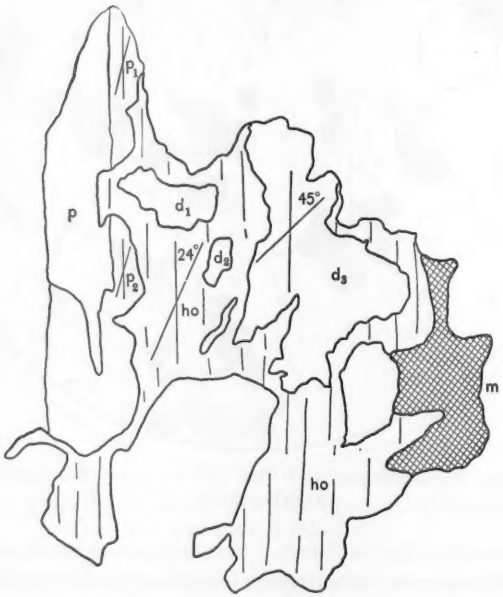

FIG. 96. Diopside (*d*) and hornblende (*ho*) (No. 1), × 50.
p = plagioclase, *m* = magnetite.

seem to be original constituents, at least they are not alteration products of any minerals present in the slide. Tourmaline is present in one rock (no. 12). The ore minerals occur mostly between the silicate minerals (Fig. 93) and careful study proves that they are later and have replaced the silicate minerals. (See Figs. 108–110.)

An interesting petrographic feature, aside from the occurrence of the ores, is that often the hornblende occurs on the border of

FIG. 97. Diopside (*d*) and hornblende (*ho*) (No. 13). *p* = plagioclase, *hy* = hypersthene, *m* = magnetite.

the diopside, not as an intergrowth or ordinary alteration product, yet formed at the expense of the diopside. Figs. 96 and 97 illustrate these hornblende areas (*ho*) with cores of diopside (d_1, d_2, d_3), different parts of which extinguish together. The plagioclase (p, p_1, p_2) also seems to have been replaced by the hornblende. The evidence suggests that the hornblende-plagioclase rock (diorite) was formed from a diopside-plagioclase rock (gabbro) perhaps by magmatic gases. The change of diopside to hornblende seems to have been accompanied by the introduc-

tion of interstitial quartz, for of seven rocks containing quartz all but one contain hornblende. Four slides with diopside also have hornblende, while hypersthene often occurs without hornblende. The magmatic alteration of pyroxene to amphibole has been described by Becke,[1] Duparc,[2] and de Lapparent.[3] The frequent occurrence of hornblende in gabbros may perhaps be explained by the magmatic alteration of pyroxene to hornblende.

Several alteration products of the silicates were found and while they are not usually prominent they probably mark important stages in the history of the ore-deposit. They will be discussed later.

Grano-diorite.—One of the fine-grained rocks (no. 11) is decidedly more acid than the others. It consists essentially of plagioclase, microcline, quartz, and biotite with subordinate amounts of apatite, titanite, epidote, chlorite, calcite, analcite, and ore-minerals. The minerals are all fresh with very little alteration (slight sericitization of the feldspars and slight chloritization of the biotite). The plagioclase is andesine, about Ab_2An_1, as determined by the maximum extinction of 15° in sections normal to the albite twin-lamellæ. The microcline occurs in comparatively small anhedra and was formed later than the plagioclase. The quartz is interstitial and also occurs with feldspar in myrmekitic intergrowths. Calcite and analcite, apparently original constituents of the rock, are among the last minerals to form.

Biotite-rich Grano-diorite.—Several of the rocks (no. 12, no. 15 and no. 40) are like no. 11 but contain a good deal of biotite or chlorite, which is an alteration product of the biotite. The presence of biotite (or chlorite) seems to favor the development of the primary ore minerals. Tourmaline occurs in no. 12 in aggregates of blue and brown subhedral crystals.

These grano-diorites are evidently differentiation products of the norite-diorite.

[1] Tschermak's "Min. u. Petr. Mitth.," Vol. 16, p. 327.
[2] *Bull. fr. soc. Min.*, Vol. 31, p. 50, 1910.
[3] *Bull. fr. soc. Min.*, Vol. 33, p. 254, 1908.

Pegmatite.—The pegmatites (no. 3) are narrow (one to two inches in width) veins consisting mainly of albite (maximum extinction angle of 19° in albite twins) and quartz. The albite is not lamellar like the albite of most granite-pegmatites. The quartz occurs in part as graphic intergrowth with plagioclase. Calcite, analcite, and chlorite are present, not as alteration products of any minerals present in the slides, but as pneumatolytic or hydrothermal minerals, formed at a late stage. Epidote occurs in small anhedra closely associated with the ore minerals. The ore minerals, chalcopyrite and bornite, occur in vein-like arrangement unlike the disseminated specks of ore in the main rock. The bornite is sometimes bordered by a secondary rim of chalcocite.

PRIMARY ORE MINERALS.

There are six opaque minerals in the ores from the Engels mine, viz., magnetite, hematite, chalcopyrite, bornite, covellite, and chalcocite. Of these the first four are primary[1] and the last two secondary.[1] The absence of pyrite from the ores and rocks is a remarkable feature of this ore-deposit.

Magnetite is present in all the specimens except the pegmatite (no. 3). It has a rough surface and occurs in both subhedral crystals and in anhedra. The subhedral crystals occur within the silicate minerals and the anhedra occur for the most part around the silicates.

Hematite occurs in anhedra with rather smooth surfaces showing faint scratches. After dissolving the non-magnetic concentrates in nitric acid to free from copper sulphides the aqua regia solution gives tests for iron only. Hematite and anhedral magnetite are usually closely associated (Fig. 106).

Bornite and *chalcopyrite* occur in anhedra and are easily recognized by their color. They are often closely associated and are evidently practically simultaneous for outliers of bornite occur in the chalcopyrite and vice versa.

The primary ore-minerals were undoubtedly formed later than most of the silicates.

[1] Primary and secondary are used in a mineralogical sense.

SECONDARY ORE MINERALS.

Three secondary copper minerals, viz., chalcocite, covellite, and chalcopyrite have been identified in polished sections. These three secondary minerals are clearly alteration products of bornite, but not of chalcopyrite.

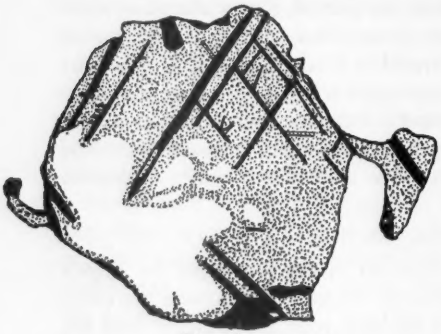

FIG. 98.

FIG. 100.

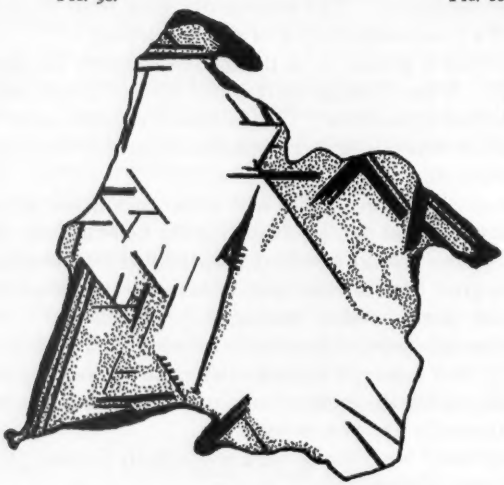

FIG. 99.

FIGS. 98, 99, 100. (No. 11.) Covellite (solid black) and chalcocite (stippled) developing from bornite (white).

Covellite.—In a number of specimens (nos. 11, 14, 16, 18, 24, and 28) the disseminated specks of bornite are penetrated by deep blue acicular crystals of covellite.[1] When examined in reflected light with one nicol in the microscope tube the covellite shows a pseudo-pleochroism from deep blue (elongation parallel to the vibration plane of the nicol) to light blue (elongation perpendicular to the vibration plane of the nicol). The replacement of bornite by covellite is evidently along crystallographic directions of the bornite for the orientation of the covellite is often uniform in several directions over the whole area of bornite.

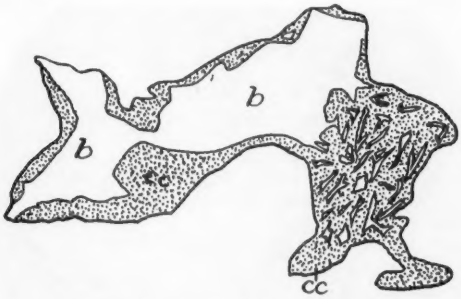

FIG. 101. (No. 12.) Bornite (white) altering to chalcocite (stippled).

Sketches of the covellite replacement of bornite are shown in Figs. 98, 99 and 100. The crystals of covellite intersect at angles of 60°, 70° and 90°. These angles indicate respectively two-fold, three-fold, and four-fold directions of symmetry of the isometric system since bornite is an isometric mineral.

Chalcocite usually occurs as a rim around bornite. It is clearly a metasomatic replacement of bornite for various stages of the process may be traced. Fig. 102, for example, shows a very narrow rim of chalcocite around the bornite. Fig. 101 represents

[1] There seems to be a strong tendency for covellite to form euhedral crystals even when replacing another mineral. Specimens from Butte, Montana, and from the Nevada-Douglas mine, Lyon county, Nevada, furnish good examples.

EXPLANATION OF PLATE IV.

FIG. 102. Bornite (white) alternating to chalcocite (No. 12).
FIG. 103. So-called intergrowth of chalcocite and bornite (No. 12).
FIG. 104. The development of sericite and the break-down of bornite into chalcocite (No. 39).

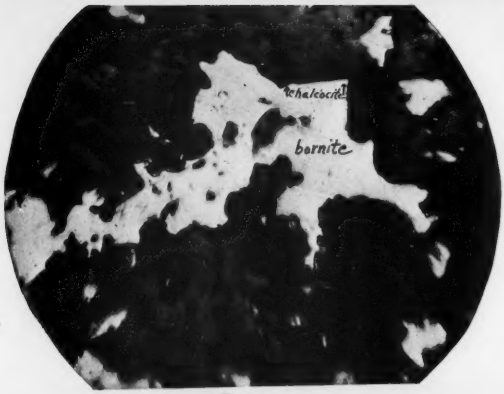

FIG. 102.

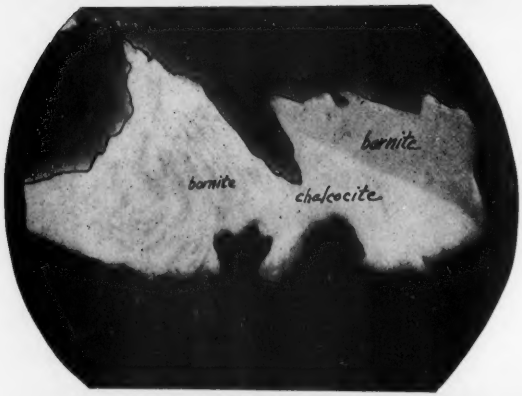

FIG. 103.

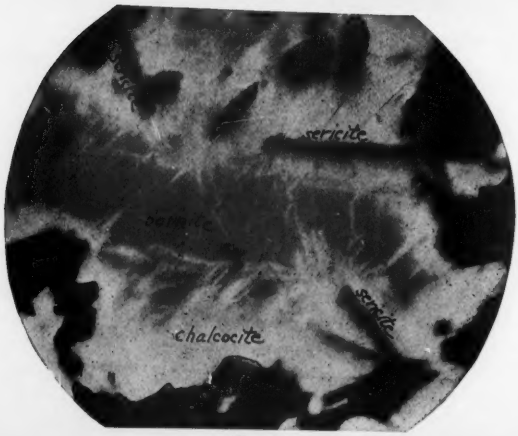

FIG. 104.

a more advanced stage. Chalcocite was identified in specimens nos. 3, 12, 15, 30, and 39. A chemical analysis of chips from specimen 39 gave Mr. G. W. Jordan the following results:

		Molecular Ratios.
Cu	43.95	0.691
Fe	5.12	0.109
S	14.15	0.472

As chalcocite is the only copper mineral with a Cu to S ratio greater than 5:4 (bornite $= Cu_5FeS_4$) this analysis is conclusive proof that the dark rim around the bornite is chalcocite. The analysis on recalculation proves that the chalcocite contains about 6 per cent. of iron for chalcopyrite is absent and the nitric acid solution used would not dissolve magnetite or hematite. Assuming that the sulphur has remained constant the analysis proves that there has been a loss of iron and gain of copper.

The alteration of bornite to chalcocite is not always regular. In specimen no. 12, for example, the chalcocite is irregularly disposed with reference to the bornite and occasionally there is what seems to be a graphic intergrowth of bornite and chalcocite (Fig. 103). A careful study of the polished section shows that this supposed intergrowth is simply a peculiar break-down of bornite into chalcocite for there are all stages from narrow rims of chalcocite to the apparent intergrowth. It is doubtful whether a graphic intergrowth of chalcocite and bornite really exists. Fig. 104 from specimen no. 39 shows the breaking down of bornite into chalcocite along crystallographic directions. In Fig. 23 of Graton and Murdoch's paper on "The Sulphides Ores of Copper"[1] crystallographic directions are also apparent.

The covellite previously mentioned is practically always associated with chalcocite. Figs. 98 to 100 show that the crystals of covellite are bordered by chalcocite. The chalcocite is later than the covellite and forms at its expense though there is evidence that the chalcocite may also form directly from the bornite. A

[1] *Bulletin Amer. Inst. Min. Eng.*, May, 1913, p. 793, fig. 23. A better cut from the same negative is given in Lindgren's "Mineral Deposits," p. 814, fig. 251.

little secondary chalcopyrite is produced in the alteration of bornite to covellite and chalcocite. The covellite seems to be responsible for the presence of chalcopyrite for it occurs along the acicular crystals of covellite and seems to be later than the covellite.

That the mineral accompanying covellite is chalcocite is proved by a partial analysis of specimen no. 11 made by Mr. G. W. Jordan:

		Molecular Ratios.
Cu	3.87	0.61
S	1.48	0.46

Though chalcopyrite, bornite, and covellite are all present the high Cu to S ratio proves that chalcocite must be present.

Specimen no. 15 exhibits a pale blue mineral occurring as rims around, and as stringers in, bornite. With a high power objective the acicular structure of covellite is apparent but the pale blue color indicates that chalcocite is also present. A partial analysis of chips made by Mr. G. W. Jordan gave the following results:

		Molecular Ratios
Cu	29.67	0.46
Fe	9.12	0.16
S	12.89	0.40

A recalculation of this analysis indicates that both covellite and chalcocite are present. The pale blue substance is probably an intimate mixture of covellite and chalcocite. Such mixtures have been described under the names digenite and carmenite. Professor J. D. Clark, working in the chemical laboratories of Stanford University has proved that covellite changes to chalcocite even at ordinary temperatures.

The alteration of bornite, then, is of two types, directly to chalcocite, or to chalcocite through the intermediate stage of covellite.

SEQUENCE OF MINERALS.

An attempt is here made to trace out the history of the Engels ore-deposit from the early magmatic stages to the present condi-

tion. The sequence of minerals is about as follows, though the exact position of a few minerals is in doubt.

SEQUENCE OF MINERALS.

1. Magnetite (euhedral) 2. Apatite 3. Hypersthene 4. Diopside 5. Plagioclase (Ab_1An_1)	*Early Magmatic Period.*
6. Hornblende 7. Quartz (interstitial) 8. Magnetite (anhedral) 9. Hematite 10. Talc (?) with secondary magnetite. 11. Tourmaline. 12. Chlorite 13. Chalcopyrite 14. Bornite 15. Epidote	*Late Magmatic Period.* (Mineralizers active.)
16. Sericite 17. Covellite 18. Chalcopyrite (secondary) 19. Chalcocite	*Hydrothermal Period.* (Ascending sulphide enrichment.)

The first five minerals enumerated belong to the early magmatic period. They follow the normal order of crystallization of Rosenbusch.

Before the norite-diorite was completely solidified the magmatic alteration of diopside to hornblende took place. This was probably accompanied by the introduction of magnetite and hematite. Fig. 105 is introduced as evidence. A narrow rim of hornblende occurs as a kind of reaction-rim between the ores and the diopside.

The hypersthene is often altered to a gray indefinite substance with aggregate structure. It does not seem to be uralite or bastite, but is probably talc. Accompanying the formation of this substance secondary magnetite is set free which is strong presumptive evidence that it is talc. The hypersthene free from the ore-minerals often shows this alteration product, while in rock

no. 16 the hypersthene with abundant ore-minerals shows practically no alteration. For this reason the talc (?) is placed after magnetite and hematite.

FIG. 105. Reaction rim of hornblende (*ho*) around diopside (*d*) (No. 14), × 27. *p* = plagioclase, *h* = hematite, *m* = magnetite.

Tourmaline and chlorite apparently fall between the period of magnetite-hematite formation and that of chalcopyrite-bornite. In specimen no. 12 bornite is clearly later than tourmaline. The chlorite in this specimen probably belongs to the same period as

tourmaline and is evidently an alteration product of biotite on account of the presence of sagenite webs of rutile. The intense mineralization which caused the local development of tourmaline probably also brought about the complete chloritization of the biotite in this particular specimen. A careful study of no. 12 seems to indicate that the development of the bornite took place later than the chloritization for the bornite is often developed along a line of rutile needles. A veinlet of chlorite in specimen no. 18 cuts through magnetite and hematite but is cut by bornite.

The evidence is that chloritization preceded, but was independent of, chalcopyrite-bornite formation for specimen no. 15 contains a large amount of unaltered biotite with very little chlorite yet both chalcopyrite and bornite are abundant. In specimen no. 40 bornite has invaded a biotite-chlorite crystal in which the chlorite is an alteration of the biotite, yet the biotite and chlorite are equally affected. Chlorite is probably a pneumatolytic mineral. It is an alteration product but so is the hornblende. These minerals are high-temperature magmatic alteration products and so they are assigned to the late magmatic period.

Though a little later than the chlorite the chalcopyrite and bornite are to be considered magmatic minerals. They were formed at the very last stages of the magmatic period. They have been formed by a metasomatic replacement of the silicate minerals but this replacement does not seem to have been connected with any kind of hydrothermal alteration. The silicates, into which chalcopyrite and bornite penetrate, and which they surround, are usually entirely free from alteration.

Epidote is considered to mark the close of the magmatic period. Analcite and calcite also belong here but their exact position can not be fixed.

At a little later stage we have the alteration of bornite into chalcocite or into a mixture of chalcocite or covellite. The chalcocitization and covellitization is accompanied by sericitization. Most of the rocks which contain sericite also contain chalcocite or covellite. The specimens richest in chalcocite [nos. 12, 15 (Cu = 29.7 per cent.), and 39 (Cu = 43.9 per cent.)] contain

notable amounts of sericite. In the specimens mentioned sericite crystals penetrate into the chalcopyrite and bornite (Figs. 104, 106 and 107). The sericite has evidently replaced the chalcopyrite and bornite. As far as I know the replacement of sulphides by sericite has not been described before. Most of the sericite is in slender lath-shaped crystals and is not an alteration product of biotite or chlorite, for they occur in stout, thickset crystals. In specimen no. 12 the feldspars have been some-

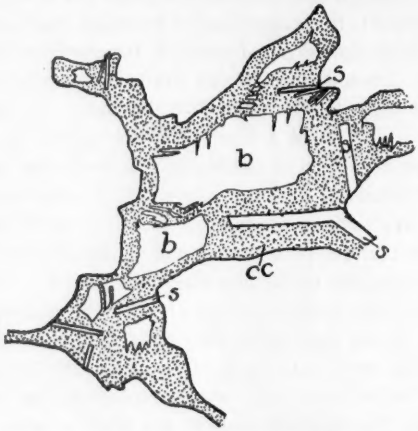

FIG. 106. (No. 39.) Sericite (*s*) with bornite (white) and chalcocite (stippled).

what sericitized. Where the sericite has penetrated bornite a rim of chalcocite or covellite has developed. This is very apparent in Fig. 107. Strange to say, the penetration of chalcopyrite by sericite has had no effect. This points clearly to the formation of chalcocite and covellite by a hydrothermal process. Chloritization apparently has nothing to do with sericitization for in no. 15 there is much sericite but very little chlorite.

At and near the surface there was some oxidation by meteoric waters with the development of chrysocolla as pointed out by Mr. Turner.

A study of the list of minerals on page 383 indicates a progressive decrease of temperature from ordinary fusion perhaps through aqueo-igneous fusion to hydrothermal solutions and finally to cold surface waters.

MAGMATIC ORIGIN OF THE PRIMARY ORES.

The evidence presented in the preceding page leads to the conclusion that the primary ore-minerals (magnetite, hematite, chalcopyrite, and bornite) of the Engels deposit were formed toward the close of the magmatic period by a partial replacement of the silicate minerals. The absence of distinct crystal outlines and the

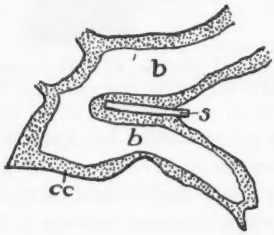

FIG. 107. (No. 15.) Rim of chalcocite (*cc*) around bornite (*b*) and between bornite and sericite (*s*).

more or less hook-shaped anhedra of Fig. 94 suggests replacement. Notice the irregular character of the bornite in Fig. 108. As additional evidence of this replacement figures 108 to 110 are presented. In Figs. 108 and 110 the two parts of the feldspars *f* and *f'* extinguish together showing clearly that they each represent a single individual crystal. In Fig. 109 the invasion of biotite by the ore-minerals is unmistakable. It is significant, however, that ores usually occur around the silicates and only occasionally penetrate them. Biotite seems to be especially susceptible to replacement.

About the only conceivable way in which the replacement of silicates by the ore minerals could have taken place and still leave the silicates unaltered is by means of gaseous solutions. The ore-

bearing solutions were probably rich in mineralizers. The most effective mineralizer was probably sulphur which was accompanied by water as shown by the presence of hornblende, chlorite, and analcite. The presence of tourmaline in one slide and the occurrence of pegmatites prove that mineralizers were active.

FIGS. 108 (No. 11), 109 (No. 11), 110 (No. 16). The replacement of feldspars (*f*) and biotite (*b*), by ore materials (solid black).

The reversal of the normal order of crystallization, *i. e.*, the formation of the ore-minerals after most of the silicates were formed, was probably due to the presence of mineralizers.

The introduction of the primary ores was accompanied by, or connected in some way with, a partial differentiation of the magma. The ores occur in norite-diorite, a rather basic igneous rock, yet some of the rocks contain interstitial quartz and the richest primary ores are in rocks more acid than the average. The copper was probably extracted from a magma basin of the composition of norite. The extraction and consequent concentration of the copper as well as the accompanying differentiation was probably brought about by gases above the critical temperature of water. The non-uniformity of the rocks and the variation in grain can thus be accounted for.

When the Engels ore deposit was first studied there was a tendency to separate it from the magmatic segregation type under the name magmatic extraction. This term, however, has been used by Geikie[1] in a different sense. De Launay[2] also uses an

[1] "Field and Structural Geology," 2d edition, p. 268, 1908.
[2] "Gites Minéraux et Métallifères," Vol. 1, pp. 22, 83, 1913.

almost equivalent term "Gites de départ immidiat" for some of the magmatic sulphides. On closer study, it was realized that practically all the magmatic sulphide deposits are essentially of the type here described.[1] In the Sudbury, Varallo, Erteli, Sohland, Insizwa, and Little Namaqualand deposits the sulphides have been formed at a late magmatic stage by a partial replacement of the silicates. The introduction of the sulphides has usually been accompanied by the introduction of quartz and feldspars. This is very marked at Sudbury where a norite gradually passes into a micro-pegmatite. This explains why some authors, notably Dickson,[2] have assigned an epigenetic origin to the Sudbury ores.

ASCENDING SECONDARY SULPHIDE ENRICHMENT.

In a recent number of ECONOMIC GEOLOGY[3] the writer proposed the idea of secondary sulphide enrichment by ascending alkaline waters though it had been hinted at by Weed[4] some years ago. This paper was based upon a preliminary study of specimens from the Engels Mine. The evidence derived from a more complete study of both thin sections and polished sections tends to strengthen my belief in ascending sulphide enrichment.

About ten rock or ore specimens show chalcocite or covellite, both of which minerals are undoubtedly formed at the expense of bornite by metasomatism. The development of these minerals belongs to the hydrothermal stage for the chalcocitization of the bornite was accompanied by sericitization, but not by kaolinization. For this and other reasons chalcocite enrichment in the Engels Mine is thought to be due to ascending, rather than to descending, solutions, as sericite is one of the characteristic hydrothermal minerals. None of the geological evidence presented by Mr. Turner controverts this view

[1] Prof. C. F. Tolman, Jr., and the writer have begun a study of the magmatic sulphides and will welcome any specimens of magmatic ores or igneous rocks which show original sulphid minerals.

[2] *Trans. Am. Inst. Min. Eng.*, Vol. 34, p. 3, 1904.

[3] Vol. VIII., pp. 781–794, Dec., 1913.

[4] *Trans. Am. Inst. Min. Eng.*, Vol. 33, p. 747, 1902.

while much of it tends to support it. That chalcocite may form from alkaline solutions is proved by experiments made by Prof. J. D. Clark working in the chemical laboratories of Stanford University.

Out of ten or twelve specimens which contain covellite or chalcocite only three (15, 28, 39), according to Mr. Turner, have any evident connection with oxidation. Of the others four or five occur in no. 5 tunnel in the hard, dense rock well to the northeast of the faulted zone shown in Fig. 91. Specimen no. 12, for example, according to Mr. Turner, is "primitive unoxidized ore. It does not occur along any seam which would permit the downward percolation of oxidizing waters."

In several slides studied by the writer there are a few opaque spots which may possibly contain kaolin, and there is an "iron stain" which is probably due to the hydration of hematite. But these are very minor occurrences, and, what is even more significant, they occur in specimens which contain little, or no, chalcocite and are absent from the specimens which are richest in chalcocite. The evidence of oxidation in specimens containing chalcocite is no proof that descending enrichment took place, for the oxidation may have taken place after the ascending enrichment. The occurrence of rich chalcocite-bearing ores (nos. 15[1] and 39[1]) near seams along which there was some oxidation is no argument in favor of downward enrichment for chalcocite also occurs in hard, dense rocks where there was no possibility of oxidation. The intimate connection of chalcocitization with sericitization in the Engels Mine is, in my opinion, conclusive proof of secondary enrichment by ascending alkaline solutions. This may conveniently be called *sulphide enrichment* in contradistinction to the term *downward*.

[1] The ascent of hydrothermal solutions probably took place readily along the leached zone (Fig. 91) and along seams (Fig. 92) but practically no chalcocite deposition took place except around bornite. This will explain the occurrence of these rich ores near post-mineral fractures (*i. e.*, post-primary mineral fractures).

CONCLUSIONS.

Two points which may be of importance in the general theory of ore-deposits have been brought out in this paper.

1. In ore-deposits of magmatic origin the sulphides may be formed during the very last stages of the magmatic period.

2. Secondary changes in primary sulphide minerals (especially copper sulphides) may be brought about by ascending alkaline waters, thus producing what may be called ascending (secondary) sulphide enrichment.

These two points have been established by a careful microscopic study of the ores and rocks. The microscope will undoubtedly play an important part in the future study of ores.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

HYDROTHERMAL ALTERATION OF GRANITE.

Sir: In Number 8, Volume VIII., of this journal there appears a criticism by W. L. Uglow of my article on "The Hydrothermal Alterations of Granite and the Source of Vein-Quartz at the St. Anthony Mine." Before replying in detail to the different items of the criticism, I might explain how the chemical analyses were obtained.

It was my original intention to publish only a petrographic description of these rocks, but Professor Logo stated that he had a number of students who had made analyses and whom he considered capable of analyzing a rock for the more common constituents. The powdered samples were, therefore, submitted and the analyses made by those students under Professor Logo's direction. In the first set of analyses the percentages of the rarer constituents were also obtained, but we did not deem it wise to publish them unless they were determined by experienced analysts. Being surprised at the high proportion of soda when compared with potassium, and having to leave for the field about the time the results were received, the matter was left over until the next year and the same set of specimens under different numbers was submitted to another class of students, and in this case only the common constituents were determined. While these results differ a little in total and in the percentage of some of the constituents, they were very similar in most respects, and the ratio

of potassium to sodium was the same as in the other analyses. The publication of these analyses, therefore, seemed justified although they were not regarded as of the highest grade.

Under heading 1 of Mr. Uglow's criticism, he attacks my calculations of the volume changes which have occurred in the alteration. In my statement there was no intention to convey the idea that a certain amount of feldspar had always altered to a known volume of secondary minerals, but rather that from the relations between the areas of thin sections from the different types, and the chemical analyses one can account for the higher percentage of certain constituents in the sections, and, therefore, in certain volumes of the altered rock. Mr. Uglow cites Mr. Mead's paper, but I agree entirely with Mr. Mead in his statement that in hydrothermal alterations there may be addition and subtraction, and that unless all the factors be known, it is impossible to apply in detail these methods of calculation. In the same section of his article Mr. Uglow suggests a possible explanation of the unusual relation between the percentage of K_2O and Na_2O as if it were an original idea, whereas if he had referred to page 757 of the article, he would have found that this matter had already been discussed but with the additional advantage of some acquaintance with the field relations.

As to the occurrence of a higher percentage of soda in these rocks than in other cases, the writer does not attempt to speak with authority on the subject, but it does seem reasonable that if the original rock were high in soda-bearing feldspars, and under requisite conditions these altered to a comparatively stable condition, in the form of secondary mica, the altered rock might be high in soda. In discussing this matter recently with a well-known mineralogist, he stated that he had found paragonite developed by metamorphism and that he did not regard this case as impossible.

Under section 2 of Mr. Uglow's article, some exception may be taken to the criticism in that, owing to the fact that only a portion of the minerals stated by me are named, a wrong impression might be obtained by anyone who read the criticism and was not familiar with the original paper.

This statement is made that no determination of H_2O, P_2O_5, F and Cl has been made, and that the analysis totals 99.63 per cent. If Mr. Uglow were familiar with rock analysis, he would know that when the phosphorus is not determined, it is reckoned with the alumina, and its determination would not, therefore, increase the total. Furthermore, if the analysis shows the presence of Cl, F or S a certain amount must be deducted as the oxygen equivalent and, according to Washington, this is 0.22 times the percentage for Cl and 0.42 for F. Taking these things into consideration, I do not see that the total in this analysis should worry anyone, especially as Washington states in his text "The Chemical Analysis of Rocks," page 23, that in the usual run of analytical work a satisfactory analysis may run from 99.5 to 100.75 per cent.

Having recently had determinations for water above 105° made, it was found that the following percentages of water were present. Specimen No. 337, 0.32 per cent., No. 336, 1.75 per cent., and 335, 1.92 per cent. In the recalculation of No. 337, I readily admit that the alumina is too high and this is no doubt due to an error so often made by inexperienced chemists of allowing some silica to be carried down with the alumina. In looking up the first analysis of this specimen, I find that the alkalies are a little higher and the alumina a little lower than in the analysis published, although the ratio of the alkalies in the two analyses is almost identical. If we allow more of the potash to be reckoned as muscovite, than that allowed by the two-to-one ratio for water and potash of the theoretical composition, and this would be quite justified from the evidence offered when various analyses are considered, it would also reduce the excess of alumina a little.

Checking up the petrographic analysis there are no minerals additional to those named, and the only change I would have any desire to make in my original statement would be to slightly reduce the relative importance of the apatite.

In the consideration of No. 336 a re-examination of the thin sections verifies my previous conclusions and I do not accept Mr. Uglow's criticism of this specimen, because by assigning the

water (1.75 per cent.) to paragonite or part of it to sericite and then assigning the remainder of the alkalies to microcline,—quite a legitimate action since the soda in microcline may vary from zero to a percentage almost as great as that of the potash,—the analysis checks up very satisfactorily.

The recalculation of No. 335 is not satisfactory, and the writer is at a loss to explain it. The alkalies are evidently too high, but they are in both of the analyses of this specimen made at different times and by different men. The determination of water gave 1.92 per cent. and this would correspond more nearly with the percentage of the alumina. In calculating the percentage composition of complex compounds such as the micas, a good deal of latitude may be allowed, judging from various analyses which show the alumina content of sericite to vary from 19.28 to 36.76 and that of potash from 4.41 to 11.67 per cent., nevertheless this is not offered here as a satisfactory explanation. It is also possible, however, that some feldspar in small grains occurs with the quartz and scaly mica in such intimate mixture that it cannot be recognized under the microscope, and this might account, to some extent, for the high percentage of the alkalies and low percentage of the alumina and water in an analysis of a considerable mass of the rock.

While admitting defects in the chemical analyses since they were not made by expert chemists, these do not affect materially my conclusions, since they are supported fully by mineralogical determinations and field observations. Furthermore, the most important item of the chemical analyses, namely, the ratio of the potash to the soda, seems to be substantiated because even if the percentage of the alkalies be not exact the method employed in analysis would cause the error to lie on the side of low soda and high potash rather than in the opposite direction.

E. S. Moore.

IS THE BOULDER BATHOLITH A LACCOLITH?

DISCUSSION[1] OF PAPER BY A. C. LAWSON.

Sir: Professor A. C. Lawson has recently published a paper entitled "Is the Boulder Batholith a Laccolith? A Problem in Ore Genesis,"[2] which is of much interest to economic geologists for several reasons: and this interest is heightened by the fact that Professor Lawson is one of few vigorous opponents of the theory of the magmatic derivation of ore deposits. In this publication he challenges the current interpretation that the great granite intrusion in southwestern Montana, known as the "Boulder Batholith," is a batholithic mass. He reaches the conclusion that it is in reality an irregular transgressive laccolith. From this conclusion he believes that certain consequences important to the theories of ore genesis follow as necessary deductions. Of these, the most important is that the metalliferous lodes causally related to the intrusion of the Boulder mass were deposited by ascending hot waters of meteoric origin. It is my purpose here to discuss some of these deductions.

The distinction between a laccolith and a batholith is first clearly defined by Professor Lawson. A laccolith is essentially an injected mass resting upon a bottom or underlying partition; a batholith, on the other hand, differs fundamentally from a laccolith in that it is not injected, and that whatever the nature of the bottom on which it rests, it has not come to place upon that bottom by moving over it, but by being developed above it. The Sudbury laccolithic sheet, the Duluth gabbro laccolith, and the Bushveld laccolith are cited to prove that mere size is no argument against the laccolithic nature of the Boulder mass. Certain structural evidence is then adduced, principally based upon brief and rather general statements by Sales and Barrell, at first glance somewhat conflicting in character, and upon interpretations of the geologic maps accompanying Professional Paper 74 and Bulletin 527 of the U. S. Geological Survey. From this evidence

[1] Published with the permission of the Director, U. S. Geological Survey.
[2] Univ. Calif. Publ. Bull. Dept. Geol., Vol. 8, pp. 1–15, 1914.

the conclusion is derived that "the deformation of the strata and the invasion of the granite were in a broad sense coincident manifestations of a general diastrophism, and that the synclinal structure of the rocks surrounding the Boulder mass is genetically connected with the development of the latter." Here I may cite some structural evidence from first hand observations. The prevailing rocks beneath which the Boulder mass was intruded consist of series of bedded andesitic and latitic lavas and breccias. On the north end of the batholith near Helena, the rocks, however, are prevailingly of sedimentary origin, ranging from Algonkian to Cretaceous. An east-west section from Elkhorn on the east margin of the Boulder intrusive to Thunderbolt Mountain on the west shows that the rocks on the east margin dip gently to the east and that on the west margin they dip gently to the west. The line of this section crosses a remnant of the roof still remaining within the central area of the intrusion, and in this patch the strata strike in diverse azimuths and dip up to 45°. The features indicated along the line of this section are that a certain amount of doming accompanied the intrusion and that portions of the roof, as I have elsewhere pointed out, have suffered partial collapse and foundering.[1] At Helena the rocks dip in steeply toward the granite, but the contact is of a transgressive character. To the northwest, however, the prolongation of the intrusive coincides with a well-developed synclinal structure in the surrounding sedimentary rocks. The contact here, as elsewhere, is of a transgressive nature, but it is not improbable that at greater depth the sedimentary rocks pass beneath the granite and constitute a synclinal basement upon which it rests. Possibly, however, there may be a certain limited amount of laccolithic injection of the quartz monzonite along the periphery of the main batholithic mass. It may be conceded nevertheless that as a working hypothesis, the conception advanced by Professor Lawson is entitled to much weight, perhaps to as much weight as the batholithic hypothesis.

If, for the sake of argument, it be granted that the Boulder

[1] U. S. Geol. Survey Bull. 527, p. 108, 1913.

intrusive mass is essentially an irregular transgressive laccolith, does Professor Lawson's conclusion necessarily follow that the genetically associated ore deposits were formed by waters of meteoric circulation? This brings up the fundamental question of the amount of original water and other volatile constituents which granite magmas contain at the time of their intrusion. In the 40's Scheerer estimated that a magma might carry up to 50 per cent. of water, but that it was probably nearer 5 to 20 per cent. Since his time this estimate has not been fixed with any greater quantitative precision. It seems probable, however, that different magmas have different original concentrations of volatile constituents—that this is as specific a property of an individual magma as is its chemical composition—but how to obtain an independent measure of the original gas-content, we have not yet been able to devise. If appeal is made to intensity of contact metamorphism or to abundance of ore deposits around an intrusive mass as proof of a large primary content of magmatic water and other volatile constitutents, the opponents of this idea will inevitably retort that this is but arguing in a vicious circle.

In describing the relationship between the Heemskirk massif and its ore deposits, L. Keith Ward,[1] of the Tasmanian Geological Survey, comes to the conclusion that this granite intrusive, which according to usual interpretation would be termed a batholith, in reality possesses a very definite bottom above which were situated the magmatic foci, whence the ore-forming constituents were expelled. It is therefore an irregular transgressive laccolith, or to use Professor Daly's term, a "chonolith." The argument leading to this conclusion is based mainly upon the beliefs that the roots of the vein series appear to be, beyond all shadow of doubt, direct products of differentiation, and that the period of primary ore deposition, which was co-ordinate and coincident with the period of magmatic consolidation, appears to have terminated abruptly.

This is an interesting result: from the hypothesis that the

[1] "The Heemskirk massif—Its Structure and Relationships," *Australasian Assoc. Adv. Sci.*, Vol. 13, pp. 165–175, 1912.

Boulder intrusion is a laccolith, Professor Lawson deduces as a necessary conclusion that the ore deposits were deposited by waters of meteoric origin; from the hypothesis that the ore deposits of the Heemskirk intrusion are of magmatic derivation, Keith Ward deduces as a necessary conclusion that the Heemskirk intrusion is a laccolith. These conclusions, both of which emphasize how closely the problems of ore genesis are tied to our conceptions of the nature of the intrusive mass with which the ores are associated, indicate that neither one nor the other conclusion follows necessarily.

The presence of tourmaline in the Boulder ore deposits is regarded by Professor Lawson as a very strong argument in favor of magmatic emanations as a direct agency in ore deposition; but he says the argument lacks conclusiveness in the fact that the deposits under discussion are distinctly later than the intrusion of the aplites, which in turn are intruded in the quartz monzonite forming the main mass of the Boulder batholith. The charge of inconclusiveness here made applies specifically to the tourmaliniferous deposits of the Helena mining region; *a fortiori*, it must apply to the Butte deposits, inasmuch as they are not merely later than the aplite intrusions, but are also later than the granite porphyry dikes ("Modoc porphyry") cutting the quartz monzonite. The defense of the hypothesis that the Butte deposits are of magmatic derivation will be left to the geologists who have described those ore bodies, in the hope that Professor Lawson's vigorous challenge of their views will elicit a stronger presentation than they have yet attempted; and attention will now be directed to the genesis of the tourmaliniferous lead-silver deposits associated with the Boulder intrusion.

Now all that the presence of tourmaline in itself indicates is that the ore deposits containing it were formed at a high temperature. Yet, it is interesting to note, as indicating how strong traditional beliefs may become, that but one writer since the time of Sandberger, so far as I am aware, has ventured to consider tourmaliniferous deposits as formed by waters of meteoric deri-

vation. J. B. Hill,[1] during the course of the recent resurvey of the Cornish tin districts, published a paper in which he held that meteoric waters penetrated so near the region of diminishing igneous activity that solutions were effected at high temperature and deposited their constituents from the ascending currents. Stress was laid on the fact that the granite contains the necessary constituents for the lodes: tin and fluorine in the micas, and boron and fluorine in the pyrogenic tourmaline. But in the final publications on the tin districts of Cornwall, MacAlister[2] maintains the conclusion that the deposits with their tourmaline are of pneumatolytic origin and are produced by direct primary contributions from the magma. The argument must, however, appear inconclusive to the opponents of the magmatic theory, for the tin lodes cut the granite porphyry dikes (elvans) which in turn cut the granite forming the main intrusive masses.

Realizing that the presence of tourmaline in ore deposits does not of itself necessarily prove the magmatic derivation of the ore-forming solutions, I attempted, in sketching the genesis of the tourmalinic silver-lead deposits associated with the Boulder intrusion, to indicate the line of descent of the solutions and to show by what process of magmatic concentration they originated.[3] The fact that the ore deposits are distinctly later than the intrusion of the aplite, instead of being an element of weakness in the chain of reasoning, appears to be distinctly an element of strength, for the evidence shows that the aplites represent a stage of magmatic differentiation intermediate between the quartz monzonite and the ore-forming solutions. The formation of the aplite magma, which took place by fractional crystallization, was manifestly accompanied by a magmatic concentration of tourmaline, and at certain localities the aplite is filled with tourmalinic nodules

[1] "The Plutonic and Other Intrusive Rocks of West Cornwall in their Relation to the Mineral Ores," *Royal Geol. Soc. Cornwall*, Vol. 12, pp. 546–615, 1901.

[2] Hill, J. B., and MacAllister, D. A., "The Geology of Falmouth and Truro and of the Mining District of Camborne and Redruth," Geol. Survey England and Wales Memoir, pp. 167–171, 1906.

[3] "Ore Deposits of the Helena Mining Region, Montana," U. S. Geol. Survey Bull. 527, pp. 51–53, 1913.

of pyrogenic origin. The composition of these nodules, consisting as they do of silicon, aluminum, boron, iron, and potassium, is singularly like that indicated for the composition of the ore-forming solutions as shown by the metasomatic alterations that they effected in the wall rocks of the ore deposits. The tourmaline-bearing nodules were regarded, therefore, as in essence globules of the differentiate from which the ore solutions were derived, and which had congealed within the magma at the centers at which they were collecting.

Essentially this same argument had been previously used by L. Keith Ward in a notable paper which has since come to my attention.[1] In the Heemskirk-Comstock-Zeehan region, Tasmania, the magma that acted as ore bringer is in places characterized by the presence of enormous numbers of nodules composed of quartz and tourmaline with smaller quantities of feldspar and traces of cassiterite. Ward says:

> "The tendency for silica, aqueous, boric, and other vapors to collect in the heart of the magma was checked in some portions of the mass for reasons thus far not fully determined, and a number of small, separate, and isolated segregations of quartz and tourmaline resulted. Thus the nodular tourmaline granite was formed."[1]

An even more impressive example of this same phenomenon has recently been described from Mt. Mulatto, at Predazzo in southern Tyrol.[2] The ore deposits here are stringer lodes carrying tourmaline, quartz, apatite, scheelite, chalcopyrite, pyrite, and arsenopyrite. The granite, which is the ore bringer, contains tourmalinic nodules surrounded by pegmatitic aureoles of coarse quartz and feldspar. Some of the nodules carry apatite, scheelite, fluorite, sulphides (principally chalcopyrite), and calcite.

[1] "An Investigation of the Relationship between the Ore Bodies of the Heemskirk-Comstock-Zeehan Region and the Associated Igneous Rock." *Australasian Assoc. Adv. Sci.*, Vol. 13, pp. 148–164, 1912. This is one of a series of three papers; the publication by L. Keith Ward earlier cited is also one of this series.

[2] *Op. cit.*, p. 152.

[3] Granigg, B., "Die turmalinführende Kuyferkies-Scheelitlagerstätte am Monte Mulatto bei Predazzo (Südtirol)," *Zeitschr. prakt. Geol.*, 1913, pp. 481–497.

The nodules are clearly of pyrogenic origin and are locally arranged in the granite according to an irregular schlieren structure. The pegmatitic aureoles point to an unusually high concentration of the volatile fluxes of the magma, such as water and others, and the whole phenomenon leads inevitably to the conclusion that the nodules represent portions of the "acid extract" frozen in place. It is believed then that these examples from Montana, Tasmania, and especially that from Predazzo throw light upon the processes by which the ore-forming solutions were evolved within the cooling and consolidating magma: they afford as nearly direct a proof of the genetic affiliation of the ore deposits and the intrusive rock as can in the nature of things be reasonably expected.

ADOLPH KNOPF.

THE OCCURRENCE OF ALUMINUM HYDRATES IN CLAYS.

Sir: I have read with some interest M. G. Edwards' paper on The Occurrence of Aluminum Hydrates in Clays, in ECONOMIC GEOLOGY for March, 1913.

I quite agree with the author that aluminum hydrate may be present in many clays in at least small amounts; in fact I have held this view for some years. Moreover, the presence of one aluminum hydrate, gibbsite, has been demonstrated by one of my former graduate students,[1] who showed that it undoubtedly existed in certain highly aluminous clays from Kentucky and probably several others described in the same paper.

The point I wish to emphasize here, however, is that it is unsafe to attempt an interpretation of the mineralogical composition of clay from its chemical analysis for the following reasons:

1. Many published chemical analyses are incomplete or insufficiently differentiated. Titanium, for example, is not always separated, being left with the alumina, and may be present in amounts up to 2 or more per cent.

2. Some clays contain considerable muscovite, which if present

[1] S. L. Galpin, *Trans. Amer. Ceram. Soc.*, XIV., p. 301, 1912.

would demand some of the alumina being assigned to it. Other portions of the alumina may belong to feldspar and as Professor Galpin pointed out in his paper hydrous micas are also present, at times in considerable amounts.

3. The uncertainty of determining the relationships of alkalies present. They may belong to silicates, or they may be simply adsorbed compounds, being held in the clay by colloids.

4. I do not now place much faith in the rational analysis, which attempts to show the mineral composition of the clay,[1] partly for the reason that the method was worked out on the assumption that clays, in the case of the high grade ones at least, consisted of kaolinite, quartz and feldspar. This we now know is not always the case and until we can devise a method of rational analysis which will take into account the relative solubilities of the different minerals that may be present in a high-grade clay the present methods of rationally analyzing a clay will not give accurate results.

Mr. Edwards states that kaolinite is the most important of the hydrous aluminum silicates comprising clay. I question whether it is altogether safe to make this statement at present.

It is true, as Edwards credits me with stating, that many washed kaolins approach closely to the composition of kaolinite, but this might be true of kaolin that contained considerable muscovite.

There has been a tendency at times to assume that in those clays containing alumina in excess of that required to unite with silica in kaolinite, the hydrous aluminum silicates, pholerite, halloysite, allophane, etc., were present. This I consider risky for the excess alumina may be present in aluminum hydrate. It is, however, just as unsafe in calculating the latter, to assume that kaolinite is the chief silicate with alumina present. It is not always, for as shown by Professor Galpin in his study of flint clays, these show much kaolinite, while the semi-flint and plastic fire clays show much hydrous mica and little kaolinite.

We are not even sure that all of the silica and alumina are combined as silicates. A clay might have hydrous silica and col-

[1] Ries, "Notes on Rational Composition of Clays," *Trans. Amer. Ceram. Soc.*, IX., 772.

loidal alumina in such amounts as to give a silica, alumina, water ratio similar to that of kaolinite. Or again there might be a mixture of muscovite and aluminum hydrate, giving similar ratios, in which case the chemical calculation might show kaolinite and no aluminum hydrate.

It may be moderately safe to apply these methods of calculation to igneous rocks, where we are dealing with crystalline minerals, but it is not safe to apply them to clays for the reason that they are complex compounds, not composed entirely of crystalline matter but containing a not inconsiderable portion of colloidal substance of widely varying makeup.

What is needed at present is more detailed petrographic work on clay, and fewer deductions from the chemical analysis. In the present economic investigations of clay, very few chemical analyses are made for the reason that they throw little light on the physical properties of the material.

H. RIES.

REVIEWS

Structural Geology. By C. K. Leith. Henry Holt and Co., New York, 1913; 169 pp. + viii, with 68 text figs.

This little treatise is unique in being our first text-book on structural geology. The chapters in the thirteenth and sixteenth Annual Reports of the U. S. Geological Survey series, by Willis and Van Hise respectively, with the works of Gilbert, Spurr, and others have long been the classic references in English on most phases of this subject, and, supplemented by the pioneer papers of Heim and Carl Schmidt in the German, have even been used as texts in graduate work. But it has been left for Professor Leith to bring the important features of these together under a single cover, correlate and cross-refer, and add such excellent researches as those of Adams, on rock flowage, Hayford, on isostasy, and particularly his own comment as well as the work of himself and colleagues on rock cleavage and its field applications, earthquakes, unconformities, laboratory methods. Abundant foot-notes are given, and additional bibliographies and map-lists used as chapter endings; these features excuse much of the remarkable brevity in a work of such scope.

The table of contents is an unusually careful outline of the book, and is perhaps as useful a finding list as the somewhat generalized index. The introduction points out that the work is interpretative. "Emphasis upon geologic structures as related parts of a record or process rather than as isolated facts determines the manner of presentation of this book."

Not the least item is the matter of illustrations—some seventy in number, one fourth of them full-page. All are clearly labeled and otherwise explained, and repeatedly referred to in the text; and, where borrowed, duly accredited in the figure title.

The book presents in a fair light both sides of the problems treated. Chiefly because of insufficient evidence, however, many points are left open, though some do not seem to be exhaustively discussed. For example, under rock-flowage, though the analysis of this and other deep-seated conditions constitutes in many respects the best parts of the book, one wishes for more ample discussion and possibly more definite summaries and conclusions, if only tentative. Indeed the interested reader

will wish to have had a hundred pages more from this writer on these questions. He may perhaps wonder, on page 90, for example, whether or not Adams's conclusions as to maximum depth for porosity of granite, as given on page 10, might not explain the presence of moisture in the granite-gneiss "formed under deep-seated conditions unfavorable either to the presence of water or its introduction during deformation," so that, therefore, the upper limit for flow of this rock may be considerably deeper than the author's twelve-mile allowance. It will be noted that experimental findings have caused the author to grant a probable depth of porosity about double that of former theoretic estimations. This brings up the question in general of the relation of water to the origin of schist and gneiss. In order to get the bearing of the author's views, however, the reader must search such pages as 8, 10, 73, 90, 98, 99, 102. It seems intentional that the balancing of all available evidence is left for the research student to do, with the help of the references furnished.

While on the theoretic side attempts at a final word are generally held in abeyance, on the practical side tangible results are shown possible through application to field problems of the elementary principles controlling minor structures. The major structures are thus interpreted, and in many cases the results serve as important guides in the exploration for ore bodies, particularly of the bedded type.

The division dealing with fractures is especially helpful in its clear analysis of the more elemental principles above referred to, and which are too often obscurely understood. The ideas are here effectively illustrated by photographs of simple devices for showing the relations of stresses and strains in incompetent and competent strata, and of sawn blocks so shifted as to bring out post-fault relations. In this discussion, however, either reference or explanation seems necessary to show why, in the diagram of a thrust fault on page 33, direction of heave does not align with that specified by the more recent convention, as defined on page 32.

The text is an inspiration to elementary understanding as well as to research in the subject, and is therefore at once invaluable in undergraduate schools and indispensable in graduate work.

The proof-reading is well-nigh perfect, and though the English is at times unconventional, it is always clear, direct, and condensed. The compactness and strong get-up of the book insures it well against the hard knocks of field life.

CHARLES T. KIRK.

Principles of Stratigraphy.. By AMADEUS W. GRABAU. 8vo. 1150 pp. 264 ills. $6. A. G. Seiler & Co., 1224 Amsterdam Ave., New York.

In the preparation of this elaborate treatise the author has formulated first a very comprehensive conception of the province of stratigraphy, and has then developed his theme in accordance with it. The conception embraces all the materials of the globe and the interplay of forces which modify them; which destroy and reproduce them; and which must therefore be discussed and understood in order that the facts of structure may be interpreted and made clear. At the outset, as has been to a less complete degree the line of attack of other authors, six spheroidal layers are established of which five are concentric about an interior nucleus. The six are the atmosphere, the hydrosphere, the lithosphere, the pyrosphere, the centrosphere, and extending across the first three, the biosphere. When the six spheres have been briefly established and outlined in an opening chapter, they are each taken up and discussed in detail, so that they constitute practically the main subdivisions of the book. To these six, a seventh part is then added, which treats of the principles of classification and of the correlation of geological formations. From this brief statement the plan of the work can be grasped and its logical unity understood. In addition one may say that few papers of importance have escaped the author; and that to a degree which cannot fail to impress his own readers as remarkable, he has absorbed, formulated into a logical system, and recorded in convenient bibliographies the subject matter of which he speaks. The task has certainly been a protracted and formidable one. It has demanded all around preparation in physiography, petrography, paleontology and wide field experience. All of these the author has brought to bear upon it.

The portions devoted to the pyrosphere and the centrosphere are the briefest. In order of extended treatment then follow the principles of classification and correlation; the atmosphere, the hydrosphere, the biosphere and the lithosphere. The chapters on the lithosphere constitute the largest of the divisions of the book and contain the matter of chief interest to economic geologists.

In them our author reviews the formation of rock salt beds and the less easily explained columnar deposits; the deposition of coal; the origin of petroleum and gas; the general formation of sediments including sedimentary iron ores; terrestrial and desert deposits and many other matters regarding which it is of great interest and importance to have the last word of American and European writers. The treatment of the lithosphere, however, opens with the elaboration of a new system of nomenclature of the sedimentary rocks, based almost entirely upon words of Greek derivation and requiring practically the acquisition of a new

language for this portion of geology. While the terms beyond question give sharpness of definition to the author's conceptions and bring out strongly some things often overlooked, they have the unfortunate character of being unfamiliar and of thereby cutting him off from his audience. Despite this fact, which seems to the reviewer to be a drawback, and despite the author's undue fondness for unfamiliar terms derived from the classic languages, the six hundred pages devoted to the lithosphere contain a rich store of modern and stimulating interpretations of geologic phenomena.

In the pages devoted to the hydrosphere much matter on the composition of terrestrial waters of all sorts, on circulations, on the work of water and many other topics not easily accessible elsewhere, have been brought together. In discussing the biosphere the author is very much at home and not a few important points are brought out upon which years of special study have qualified him to speak. The general nature and classification of organisms, the latest conceptions of evolution and the methods by which its processes have been worked out, the distribution of organisms according to environments; the preservation of fossils,—many topics are discussed and summarized which are of interest to those desiring to gain or keep some grasp of biologic foundations and advances.

The pages devoted to the atmosphere furnish a valuable summary of facts and theory, and in the closing chapter on classification and correlation, an excellent further summary is given of methods and principles of work. The two brief chapters on the pyrosphere and the centrosphere are the least satisfactory in the book. The pages on the pyrosphere are entirely devoted to volcanoes and chiefly to the forms of cones and surface outbreaks; whereas the term pyrosphere, especially as established in the opening pages of the work, would suggest rather the deep-seated intrusive rocks, the differentiation of magmas and such themes as are taken up in Harker's "Natural History of the Igneous Rocks." Again in the chapter on the centrosphere, which in the opening pages is placed 76 miles and more from the surface, the author chiefly discusses earthquakes and even such very superficial phenomena as sandstone dikes and craterlets. The topic would rather call for a review of those more or less speculative conceptions which concern the inner portion of the globe. Both the pyrosphere and the centrosphere are more difficult and less satisfactory themes to discuss then the outer portions of the earth which are accessible to observation and which are undeniably the most important for stratigraphical studies. The latter are treated at length and with thoroughness.

J. F. KEMP.

SCIENTIFIC NOTES AND NEWS

THE FOLLOWING ANNOUNCEMENT recently made by the United States Geological Survey will be of interest to the readers of ECONOMIC GEOLOGY:

In order that the benefit of the Geological Survey's investigations may be given promptly to the interested public, the first results in its several fields are published in the form of short papers and preliminary reports and issued as separate chapters. Of these short reports those of economic interest will appear as "Contributions to economic geology," issued in the series of Survey Bulletins; those of more purely scientific interest, as "Shorter contributions to general geology," in the series of Professional Papers; and those on hydrology, as "Contributions to the hydrology of the United States," in the series of Water-Supply Papers. The chapters in each of these classes will form an annual volume (the pagination and plate numbers running continuously throughout), and at the end of the year there will be issued for each series a volume title-page, table of contents, index, and possibly bibliographic lists. Librarians and others to whom all the parts are furnished should preserve them as they would preserve any other serial.

AMONG THE RECENT PAPERS ISSUED BY THE BUREAU OF MINES are the following: Bulletin 79, Abstracts of current decisions on mines and mining, March to December, 1913, by J. W. Thompson. Technical Paper 35, Weathering of the Pittsburgh coal bed at the experimental mine near Bruceton, Pa., by H. C. Porter and A. C. Fieldner. Technical Paper 72, Problems of the petroleum industry; results of conferences at Pittsburgh, Pa.,

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

August 1 and September 10, 1913, by I. C. Allen. Technical Paper 74, Physical and chemical properties of the petroleums of California, by I. C. Allen, W. A. Jacobs, A. S. Crossfield, and R. R. Matthews.

AT A MEETING OF THE GEOLOGICAL SOCIETY OF WASHINGTON, held on May 13, 1914, an interesting paper was presented by Mr. G. H. Loughlin, on the Oxidized Zinc Ores of Leadville, Colorado.

THE UNITED STATES GEOLOGICAL SURVEY has recently issued a circular announcing an agreement for coöperation in the investigation of the building stone resources of the United States with the Bureau of Standards, the Bureau of Mines, and the Office of Public Roads. The scope of the coöperation and the part taken by the Geological Survey are outlined in this circular to which the reader is referred for greater detail.

DR. HEINRICH RIES, professor of economic geology in Cornell University, has been appointed head of the department of geology in that institution.

MR. JOSEPH STRUTHERS, formerly secretary of the American Institute of Mining Engineers, announces that he has accepted the office of Second Vice-President of the Johnson Electric Smelting, Inc., controlling the American rights of the Johnson electrothermic process for the treatment of zinc ores and zinciferous lead and copper ores, with offices at 18 East 41st Street, New York City.

MR. PHILIP LAWRENCE FOSTER announces that the New York office of the Exploration Company Limited of London has removed from 111 Broadway to 61 Broadway.

AT THE FIFTEENTH ANNUAL MEETING of the Geological Society of America, held in Seattle, Wash., May 21 to 23, the following papers were read: "Pre-Pleistocene Geology in the Vicinity of Seattle," by Charles E. Weaver; "The Pleistocene of Western Washington," by J. Harlen Bretz; "Geology and Metalliferous Deposits of the Altar Valley and Its Mountainous

Borders in Arizona," by J. A. Taff and W. L. Moody; "The Geology of Mt. Shasta, and a Portion of Northern Siskiyou County, California," by G. C. Gester; "Geologic Structure in Western Washington," by Charles E. Weaver; "Relation of the Tertiary Geological Scale of the Great Basin to that of the Pacific Coast Marginal Province," by J. C. Merriam; "Geology of a Portion of the McKittrick District, a typical example of West Side, San Joaquin Valley Oil Fields and a Correlation of Oil Sands of the West Side Fields, California," by G. C. Gester; "Basin Range Faulting in the Northwestern Part of the Great Basin," by George D. Louderback; "Structure of the Pierce County Coal Field of Washington," by Joseph Daniels; "The Tertiary Rocks of Oahu," by C. H. Hitchcock; "A Plea for Uniformity and Simplicity in Petrologic Nomenclature," by G. Montague Butler; "The Oregon Bureau of Mines," by Ira A. Williams; "The Relation between the Tertiary Sedimentaries and Lavas in Kittitas County, Washington," by E. J. Saunders.

IT IS WITH GREAT REGRET that we record the death of Mr. Newton Horace Winchell on Saturday, May 2, at Minneapolis, Minn. Mr. Winchell was in his seventy-fifth year. He was born in Dutchess County, New York, on December 17, 1839, and received his education at the University of Michigan, from which he graduated with a degree of A.B. in 1866 and three years later received the degree of A.M. He then became superintendent of public schools at Adrian, Mich., but remained in this character of work for only three years. In 1869 he was appointed Assistant State Geologist of Michigan, and from that time on was actively engaged in geological work.

Mr. Winchell retained his position on the Michigan Survey until 1870 and then for the following two years was assistant on the Geological Survey of Ohio. In 1872 he was appointed State Geologist of Minnesota, in which position he remained until 1900. While Assistant Geologist of Minnesota he was ap-

pointed to the professorship of geology and mineralogy at the University of Minnesota in the year 1873.

Mr. Winchell made a large number of contributions to geology and during a large portion of his life was interested also in archæological research. To both geology and archæology he has made numerous and valuable contributions.

Among Mr. Winchell's important contributions to geology are: "A Catalogue of the Plants of the State of Michigan," "Geology of Ohio and Minnesota," "The Iron Ores of Minnesota," "Elements of Optical Mineralogy," "The Aborigines of Minnesota."

Mr. Winchell was also one of the founders of the *American Geologist* which, as the readers of ECONOMIC GEOLOGY will remember, is now incorporated with this journal, and for a long time was its editor. Too much cannot be said in commendation of the many years of unselfish industry and scientific enthusiasm which Mr. Winchell devoted to geological science and it is with more than usual regret that the readers of this journal will read of his death.